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CLASSIFICATION OF INTACT STABILITY STANDARDS FOR DYNAMICALLY SUPPORTED CRAFT

FINAL REPORT

OCTOBER 1979

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
United States Coast Guard
Office of Research and Development
Washington, D.C. 20590

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16. Abstract

In recent years there has been an increasing employment of high-speed marine craft dependent on dynamic and air-cushion lift for support and stability. Existing regulations for the safety of ships and craft at sea are based upon displacement mode operation and cannot adequately be applied to high-speed craft when operating with their dynamic or air cushion means of support. As a result, the U.S. Coast Guard has begun a study of stability standards for such craft which is being carried out as part of the Coast Guard's overall Commercial Vessel Safety (CVS) Program. This report presents the results of the second (or classification) task of a four-task study of intact-stability standards. Four broad categories of dynamically supported craft are examined: Amphibious Air-Cushion Vehicles (ACV), Rigid-Sidehull Surface-Effect Ships (SES), Hydrofoil Craft & Planing Craft. The different methods by which stability in the nondisplacement mode is achieved by each of these categories is examined, along with the various stability related operational hazards to which they can be subjected. Existing stability standards are reviewed. From these examinations and from the results of the background study prepared as Task 1, the four categories of dynamically supported craft considered have been divided into classes for which the same, or similar, intact stability standards can apply. Tasks III and IV which have not yet been initiated are designed for the detailed investigation of stability parameters and for the development of recommended stability standards for one, or more, of the categories of craft examined.

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Planing Craft

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PREFACE

The work reported herein was accomplished for the U.S. Coast Guard's Office of Research and Development, Safety and Advanced Technology Division, Vessel & Port Safety Technology Branch as part of its Commercial Vessel Safety (CVS) Program. Technical direction of the work performed was provided by Lt. John C. Burson, USCG.

Very significant contributions to the contents of this report have been provided by:

> The U.S. Navy's David W. Taylor Naval Ship R&D Center (DTNSRDC), Bethesda, Md.
>
> The U.S. Navy's Surface Effect Ship Project Office (PMS 304), DTNSRDC, Bethesda, Md.
>
> The British Hovercraft Corporation, Isle of Wight, England.

The source of all background material used for the study is identified in the text and listed in the references at the end of the report.

METRIC CONVERSION FACTORS

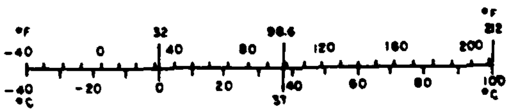
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SUMMARY

This report presents the results of the second (or classification) task of a four-task study of intact-stability standards for dynamically supported craft. Four broad categories of dynamically supported craft are examined:

- Amphibious Air-Cushion Vehicles (ACV)
- Rigid-Sidehull Surface-Effect Ships (SES)
- Hydrofoil Craft
- Planing Craft

The different methods by which stability in the non-displacement mode is achieved by each of these categories is examined, along with the various stability related operational hazards to which they can be subjected. Existing stability standards are also reviewed. From these examinations and from the results of the background study prepared as task 1, the four categories of dynamically supported craft considered have been divided into classes for which the same, or similar, intact stability standards can apply.

Tasks III and IV which have not yet been initiated are designed for the detailed investigation of stability parameters and for the development of recommended stability standards for one, or more, of the categories of craft examined.

1. INTRODUCTION

The United States Coast Guard has no special intact-stability standards for craft such as surface-effect ships, hydrofoil craft and planing craft. When such craft operate in the dynamically supported, or non-displacement mode, the present intact-stability standards for conventional craft, cannot be adequately applied. With the increasing commercial employment of high-speed marine craft, for passenger and light-freight service, and the on-going development of newer types of craft depending on dynamic-lift principles, the U.S. Coast Guard has become very much aware of the inadequacy of present regulations regarding stability for application to these advanced craft. For this reason, the Coast Guard has initiated a program of study to develop suitable stability criteria to provide the basis for standards to assure the safe operation of such craft.

The study is being carried out as part of the Coast Guard's overall Commercial Vessel Safety Program (CVS). The CVS Program objectives are directed toward minimizing loss of life, personal injuries and property damages involving commercial, scientific or exploratory vessels, both domestic and worldwide, through prevention of casualties. This objective is pursued through the administration of federal laws, the development and enforcement of Federal standards, and implementation of international agreements.

The basis for the Coast Guard safety program, with respect to foreign vessels, is a series of international agreements which include the Safety of Life at Sea (SOLAS) Convention and various other international agreements drawn up under the auspices of specialized agencies of the United Nations such as the Intergovernmental Maritime Consultant Organization (IMCO) as described by Goddu, July 72.

On the 14th November 1977, IMCO published a proposed Code of Safety for Dynamically Supported Craft* and the provisions of the code are now being studied by the member countries of the Organization. In the United States, the U.S. Coast Guard, as part of their CVS Program,are evaluating the proposed (IMCO) safety standards and, if deemed necessary, will propose amendments or new safety standards for commercial, dynamically supported craft operating in U.S. waters.

The IMCO Safety Requirements cover a wide range of considerations of which craft stability is only a part. Unfortunately, with the exception of surface-piercing hydrofoil craft, only general intact-stability guidelines are stated, eg. "Within approved operational limits, the craft should return to her original attitude after a disturbance causing roll, pitch, heave or any combination of these disturbances". It is the objective of the present study, however, to lay the groundwork for defining more specific standards.

In accord with IMCO philosophy, it was also recognized that it was necessary to produce safety standards so that

(a) Existing craft, which have demonstrated their ability to operate at an acceptable level of safety when engaged on restricted voyages and under restricted operational weather conditions, etc., were not further restricted, and that

(b) further research and development of these craft is not unnecessarily inhibited.

The fundamental principle upon which provisions were to be developed was to provide an equivalent level of safety to that nromally expected of ships complying with the International Convention for the Safety of Life at Sea, with full recognition that operational areas may have to be limited.

Proposed revisions to the IMCO Code of Safety regarding craft stability were to be investigated and formulated by the Coast Guard by means of a two phase study. Phase I was to be performed in two tasks:

Task I. Establish the background of stability of dynamically supported craft by a literature search.

Task II. Classify dynamically supported craft by susceptibility to like stability standards.

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* IMCO Resolution A 373(x), 14 NOV 1977.

If these activities suggest that effective stability standards could be developed for dynamically supported craft, the Coast Guard proposes to complete the study by a Phase II consisting of two further tasks:

Task III. Determine the effect of parameters critical to intact stability in displacement and non-displacement operation.

Task IV. Develop stability standards for one or more classes of craft.

This present report is the result of Task II. Task I was completed in June 1979 and resulted in a comprehensive six(6)-volume bibliography and a description of the findings of the background study. The six volumes were bound separately with the following titles.

Volume I. Background Study of Intact Stability Standards for Dynamically Supported Craft, Master Report.

Volume II. A Categorized Bibliography of Amphibious ACV Stability Related Reports.

Volume III. A Categorized Bibliography of Rigid-Sidehull SES Stability Related Reports.

Volume IV. A Categorized Bibliography of Hydrofoil Craft Stability Related Reports.

Volume V. A Categorized Bibliography of Planing Craft Stability Related Reports.

Volume VI. A Categorized General Bibliography of Ship and Small Craft Stability Related Reports.

This background study included the bibliographic search, document review, annotation and interpretation of the technology and requirements for stability of dynamically supported craft.

This present report, describing the results of Task II, is organized to present the background to prior stability standards, a classification of craft types and how they achieve stability, a classification of stability related hazards, a classification of stability standards and recommendations for work to be performed in Phase II of the overall study program.

The stability of four broad categories of dynamically supported craft are examined:

Amphibious Air-Cushion Vehicles (ACV)

Rigid-Sidehull Surface-Effect Ships (SES)

Hydrofoil Craft

Planing Craft

The different methods by which stability in the non-displacement mode is achieved by each of these categories is examined, along with the various stability related operational hazards to which they can be subjected. Existing stability standards are also reviewed. From these examinations and from the results of the background study prepared as Task I, the four categories have been divided into classes for which the same or similar intact stability standards can apply.

Tasks III and IV which have not yet been initiated, are designed for the detailed investigation of stability parameters and for the development of recommended stability standards for one, or more, of the categories of craft examined.

2. DEFINITION OF A DYNAMICALLY SUPPORTED CRAFT

IMCO, 14 NOV 77 recognizes dynamically supported craft by the following definition.

> 1.4.1 "Dynamically Supported Craft" is a craft which is operable on or above water and which has characteristics so different from those of conventional displacement ships, to which the existing International Conventions, particularly the Safety and Load Line Conventions, apply, that alternative measures should be used in order to achieve an equivalent level of safety. Within the aforementioned generality, a craft which complies with either of the following characteristics would be considered a dynamically supported craft:
>
> (a) the weight, or a significant part thereof, is balanced in one mode of operation by other than hydrostatic forces;
>
> (b) the craft is able to operate at speeds such that the function $\frac{v}{\sqrt{gL}}$ is equal to, or greater than 0.9. Where "v" is maximum speed, "L" is the water line length and "g" is the acceleration due to gravity, all in consistent units.
>
> 1.4.2 "Air-cushion vehicle" is a craft such that the whole or a significant part of its weight can be supported whether at rest or in motion by a continuously generated cushion of air dependent for its effectiveness on the proximity of the surface over which the craft operates.
>
> 1.4.3 "Hydrofoil boat" is a craft which is supported above the water surface in normal operating conditions by hydrodynamic forces generated on foils.
>
> 1.4.4 "Side-wall craft" is an air-cushion vehicle whose walls extending along the sides are permanently immersed hard structures.

This same definition has been adopted by the U.S. Coast Guard. Note that, although an Air-Cushion Vehicle is not in principle a dynamically supported craft, it has been qualified as such under item 1.4.1(b) of the IMCO proposed resolution.(IMCO 14 NOV 77)

In the context of this present report "Side-Wall Craft" (line item 1.4.4 of the IMCO Proposed Resolution) have been redefined as "Rigid-Sidehull Surface-Effect Ships" and (in most cases) this has been abbreviated to the term SES. Planing craft have also been included in this present study since at high speed they can often qualify under line items 1.4.1(a) and (b) of the IMCO proposed resolution.

3. REVIEW OF PRIOR WORK

Dynamically supported craft, by the definition of Chapter 2.1, were first introduced in the late nineteenth century. By 1914, planing boats had been developed sufficiently to be used successfully in World War I. It appears that hydrofoil craft, which were first introduced successfully by the Italians in 1905, were being used for military purposes by the Germans at the beginning of World War II. These craft were of the surface piercing foil type and have since been developed further, principally by Italy, the Soviet Union, Norway, Germany and Switzerland, and have been used extensively for passenger service throughout the world. The Amphibious Air Cushion Vehicle (ACV) and Rigid-Sidehull Surface-Effect Ship (SES) first appeared as viable craft in the late 1950's. By the late 1960's both types were being used extensively for passenger service, principally in Europe but also in many other parts of the world Hydrofoil craft of the fully submerged (auto-controlled) foil type were first introduced (by the U.S. Navy) in the late 1950's. Both military and commercial applications of this type have since proved very successful.

From the background work for this study, the Master Report, Volume I, presented a more in-depth discussion of these various developments, as they related to craft stability. From this background review, it was evident that very few stability related accidents had occurred among dynamically supported craft to date. Additionally, no widely accepted stability standards had been established for such craft operating in the dynamically supported mode. Stability criteria, which have been developed by private industry and governments, have ranged from the use of simple design guidelines to the use of sophisticated multi-degree-of-freedom mathematical simulations of craft motions. Seemingly because of the applicability of the use of more conventional techniques, standards for the evaluation of the stability of such craft, in the hullborne mode of operation, have been given greater publicity and have moved further towards gaining universal acceptance. (See GOLDBERG FEB, 74 as an example)

The present study relates to both displacement and non-displacement modes of operation, with emphasis placed on the latter. Since a designer and operator may well be concerned about the stability in transitioning from one mode to another, it was also considered important to review, herein, the development of stability standards for displacement craft. Also, since the development of stability standards for displacement craft have received considerable attention over the years, it was hoped that some of the basic concepts developed, particularly those developed in recent years, could be of value to guide the development of standards for dynamically supported craft.

In the subchapters which follow, the prior development of intact stability standards for each class of craft of interest is presented, starting with a review of relevant work accomplished for displacement craft (or for craft operating in the displacement mode).

3.1 STABILITY STANDARDS FOR DISPLACEMENT MODE OPERATION

The development of displacement-ship stability criteria has seen a long period of evolution which is still far from complete. According to BIRD MAR 75, one of the first measures of ship stability was the (now well known) metacentric height as developed by Piere Bouguer in 1746. In this development Bouguer first defined the metacentric radius (BM), as the ratio of water plane 2nd moment of area (I), to the immersed volume, V. (BM=I/V) Thus, the metacentric height (GM), which was used as a measure of initial pitch or heel stiffness, was defined as

$$GM = KB + BM - KG$$

where KB is the vertical coordinate of the ship's centre of buoyancy and KG is the vertical coordinate of the ship's center of gravity. Thus,ship's righting arm (GZ) was, in this case, approximated by

$$GZ = GM \cdot \sin \phi \text{ or } (GM)\phi$$

with ϕ the angle of heel in radians.

By 1796, Atwood had developed an expression for the ship's righting arm valid for larger angles of heel as follows:

$$GZ = \frac{v(h_1 \; h_2)}{V} - (BG)\sin \phi$$

In this case (v), is the volume of immersed or emerged wedge, (h_1h_2) is the moment arm of transfer of volume and (BG) is the vertical distance between the center of buoyancy and center of gravity.

It was recognized (if not at that time, then later) that (i) the (GM) should be large enough to prevent capsizing, excessive list in case of flooding or excessive list under pressure from strong beam winds and (ii) the (GM) should be small enough to prevent violent rolling in waves.

In an attempt to relate stability of ships to their rolling motion the concept of work-done to capsize was introduced by Moseley in 1850. Moseley considered the balance of work done under the influence of external forces and the work required of the ship to resist such action in terms of the area under the righting moment curve, eg. if the inequality

$$\int_{\phi_{int}}^{\phi_{max}} [M_r(\phi) - M_h(\phi)] \, d\phi \quad > \quad 0$$

was maintained, the ship was considered to be stable. In this case $M_r(\phi)$ and $M_h(\phi)$ are the functional relationships between righting and heeling moments respectively and the angle of heel. ϕ_{int} and ϕ_{max} are the initial and maximum angles of roll respectively. The general concept of this approach is still widely used.

The reader is referred to CLEARY MAR 75, HYDRONAUTICS 75 and BIRD MAR 75 for more detail concerning the historical developments in displacement ship stability criteria.

The most significant milestones and contributions which have led to the development of modern-day intact-stability criteria for displacement vessels are reviewed in Table 3-1. Of particular significance is the work by Moseley 1850, Pierrotet 1935, Rahola 1939 and Odabasi 1976. The intact-stability standards that have been developed specifically for high-performance ships operating in the displacement mode can be found in:

(i) the U.S. Navy's standards presented by Goldberg 1974 and

(ii) the IMCO Resolution A 373(x), 14 NOV 1977.

From the review of Table 3-1 and the standards given in the above references, four distinct groups of intact-stability criteria have evolved.

(a) Criteria which use GM and Freeboard and are now applied mainly to small craft, tugs and fishing vessels.(See USCG Standards for example)

(b) Criteria based on GM and the statical and dynamical righting levers as used by IMCO for example.

(c) Criteria which used simplied theoretical heeling levers for comparison with theoretical righting levers as now used by the USSR, Japan and many European countries.

(d) Newly developing criteria which are based on the theory of stability of ship motion. (See Odabasi 1976, and USCG sponsored work by Bovet 1973 and Paulling 1973)

TABLE 3-1. SIGNIFICANT MILESTONES AND CONTRIBUTIONS IN THE DEVELOPMENT OF INTACT STABILITY CRITERIA FOR DISPLACEMENT VESSELS.

YEAR	PRINCIPAL INVESTIGATOR	RELEVANT FORMULA	COMMENTS
1746	Bouguer		Metacentric radius defined.
1796	Atwood		More precise derivation of ships righting arm.
1850	Moseley		The concept of work-done to capsize established.
1887	Denny		Safe minimum stability curve recommended.
1906	BBTR		British Board of Trade Rules; gave minimum freeboard standards.
1913	Benjamin	1) $e_{60} \geq 0.656$ ft*rad for $\phi = 60°$ 2) $e_{30} \geq 0.164$ ft*rad for $\phi = 30°$	Concept of dynamical lever curve introduced as the integral of the righting arm curve. Benjamin's recommendations for minimum integral values e_{60} and e_{30} followed a comparison of a large number of vessels which had operated successfully. His limiting angles were criticized and he modified his approach to the specification of a standard curve.
1922	Biles	GM $\geq$ 1.0 Ft.	Minimum GM recommended for passenger ships. His concern was the frequent over prediction of the actual GM in the as built condition. The need to keep the period of roll longer than the encounter periods to be expected in the N. Atlantic seas is discussed.
1925	Holt		Minimum and maximum GZ's are recommended to give satisfactory initial stability and safe rolling motions from comparison with existing ships.
1929	Solas		International Convention for the Safety of Life at Sea.
1930	ILLC		International Load Line Convention. Only general guidelines given.
1935	Pierrottet		Forces tending to cause capsize are investigated. Included are the forces due to wave slope, wind pressure, passenger heel and rudder action in high speed turns. The sum of these are plotted against heel angle and are superimposed upon available righting moments. It was recommended that the destabilizing force must balance the work done by the resistive force at heel angles less than 50° for passenger ships and 25° for ferry vessels. His recommendations were not well received. They were considered to be too severe and the limiting angles were too large. The approach (in modified form) is still used today by the U.S. Navy, the Japanese and many European countries.

*originally stated in m. rad.

TABLE 3-1. SIGNIFICANT MILESTONES AND CONTRIBUTIONS IN THE DEVELOPMENT OF INTACT STABILITY CRITERIA FOR DISPLACEMENT VESSELS. (Cont'd.)

YEAR	PRINCIPAL INVESTIGATOR	RELEVANT CRITERIA	COMMENTS
1935	CWLLA		Coast Wise Load Line Act, required vessels in [illegible] service to have adequate stability
19[illegible]	Rahola	$GZ \geq$ [illegible] ft., $\phi = 20°$ $GZ \geq$ [illegible] ft., $\phi = 30°$ $GZ \geq$ [illegible] ft., $\phi = 40°$ $\phi_m \geq 35°$ Dynamical lever shall be: $e = 15$ ft. deg. for ϕ_p ϕ_r = smallest of the following (a) ϕ_m (b) ϕ for immersion of non-watertight openings (c) ϕ for shifting cargo (d) $\phi = 40°$	This was a significant contribution towards a practical criteria. Based on an investigation of the losses of Baltic coastal steamers Rahola reasoned that it was impractical to determine accurately the capsizing forces to which a ship was subjected at sea, but acknowledged that the moments resisting capsize could be adequately determined and presented in terms of GZ curves and plots of dynamical levers. His work included an investigation of 30 capsizes and the comparison of the stability of these ships with those that had not capsized by determining: - (a) The maximum allowable heeling angle for each vessel (b) The minimum required area under the righting arm curve up to the maximum allowable heel angle. (c) The required minimum area under the righting arm curve in relation to the area under the heeling moment curve. Rahola supported his investigation with maneuvering experiments to determine rudder forces and centrifugal forces in a turn. The main criticism of the criterion was that the approach was not nondimensional and could not apply equally to ships of all sizes.
1943	Taylor	$GM \geq 2.0$ ft.	For fishing vessel design a minimum initial GM is recommended for the light condition.
1947	Simpson	Freeboard $\geq$ 1.5 to 2.0 ft. GM $\geq$ 1.0 ft.	Recommended Stability Criterion for U.S. East Coast trawlers. Minimum Freeboard and GM in no-fuel condition but with 10 to 20 tons of ice on deck.
1947	Prohaska	None given.	Concept of Residual Stability introduced.
1948	SOLAS	-	This SOLAS Convention insisted that all Ship's Masters be provided with adequate stability information.
1951	Skinner	None given.	Recognition that damage stability criteria and the 1930 Load-Line Regulation for Vessels over 400 ft. in length provided adequate intact stability for large ships but not so for small vessels. Skinner considered stability of small ships under the influence of simultaneous action of wind, waves and shipping water. He concluded that the Max GZ and the corresponding heel angle were sufficient to define the righting-arm curve.
1952	Grim	$I\ddot{\phi} + \Delta(GM + \delta GM.\cos \sigma t)\phi = 0$ I = virtual mass moment of inertia about rolling axis Δ = displacement δGM = max. variation in GM σ = wave frequency t = time ϕ = angle of roll	This was the first attempt to relate the stability of a ship to its motions. It is this approach which forms the basis of most modern research activities. Grim considered the variation of restoring moment in waves using the equation shown to the left. In 1954 Grim considered the more general rolling motion as $I\ddot{\phi} + \Delta GZ(\phi) = M$ where M is the excitation.
1954	Wendel		Wendel, in combining the findings of many researchers, concluded that the most critical stability condition for ships under 200 ft length arises when the ship reacts to waves with length and velocity the same as that of the ship and with wave crest amidships. He found that the total loss of restoring moment in following or quartering waves was dependent on wave height, wave geometry, steepness and the location of the wave crest relative to the ships' length. Wendel used a graphical approach by superimposing a one-dimensional wave form on a ship's profile drawing and calculating righting arms allowing for sinkage and trim. Although some capsizes were explained by this method, it generally resulted in grossly unrealistic losses in restoring moments. This was later modified by others Arndt & Roden using the Smith Effect. (Also Pauling 1961)
1955	Kerwin		Attempted association of ship motion theory with transverse stability. Results showed that for (conditions of no damping and for ratios of the wave encounter period to the roll natural period of 0.5, 1, 1.5 etc. unstable rolling motion occurred.
1956	Steel		The effect of operational factors on ship stability were considered. After analyzing several casualties Steel concluded that the minimum standards should not be accepted without considering the type of ship, it's service and type of cargo.

TABLE 3-1. SIGNIFICANT MILESTONES AND CONTRIBUTIONS IN THE DEVELOPMENT OF INTACT STABILITY CRITERIA FOR DISPLACEMENT VESSELS. (Cont'd.)

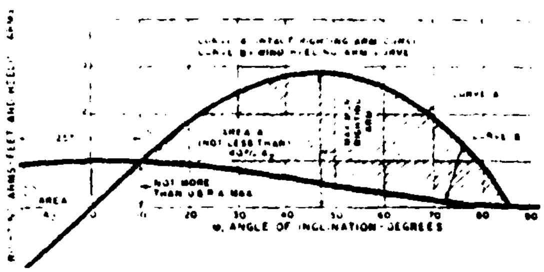
YEAR	PRINCIPAL INVESTIGATOR	RELEVANT FORMULA	COMMENTS
1959	Yamagata	See Pierrottet, 1935	Stability criteria adopted in Japan was presented. The method used was similar to that used by Pierrottet (1935). Yamagata also presented his method for calculating destabilizing and stabilizing moments.
1959	Paulling		Unstable ship motions resulting from non-linear coupling were investigated. Pitch, heave and roll equations were examined using a Taylor series expansion (terms higher than second degree discarded). Heave-roll coupling leading to instability was analytically demonstrated and verified experimentally.
1960	SOLAS		Safety of Life at Sea Convention.
1961	Paulling		In an extention of Wendel's work Paulling computed the transverse stability of a ship supported by a wave and verified his result experimentally. He recognized that stability in waves differs from the static case due to the difference in under water geometry and the non-hydrostatic pressure distribution (Smith Effect) in waves. For small angles of heel Paulling presented analytical expressions for righting arm as a function of the ship and wave geometry and for large angles he used Bonjean and moment curves and satisfied equilibrium conditions by trial and error as per methods used in bending-moment calculations.
1962	IMCO		IMCO Sub-Committee on Subdivision and stability for all ship types was established.
1962	Du Cane		Broaching and surging in following seas was studied and included experimental investigation in regular seas using a powered destroyer model in a free-to-surge rig. The phenomena of "capture" in which surging is reduced to zero and the ship is forced to proceed at wave speed, was demonstrated.
1962	Sarchin	(a) Heeling arm at point (c) $\leq$ 0.6 max righting arm. (b) $A_1 \geq 1.4\ A_2$ where A_2 extends 25° to windward of (c).	This defines the stability and buoyancy criteria for U.S. Naval Surface Ships. The assessment of adequate intact stability uses the Pierrottet (1935)(so called wind-line) approach in comparing the ship's righting arm curve and wind-heeling-arm curve and includes allowances for the movement of heavy weights and passengers, high-speed turning, and top-side icing.  The criteria, in general, represent higher standards than employed in commercial practice.
1962	Suarez		From an analytical treatment of broaching Suarez indicated conditions under which the yawing moment would increase beyond the ability of the rudder to prevent broaching.
1962	Swaan		The existence of a minimum wave steepness beyond which broaching would occur was demonstrated using simplified equations of motion in the horizontal plane. The effect of hull design on broaching tendency was also indicated.

TABLE 3-1. SIGNIFICANT MILESTONES AND CONTRIBUTIONS IN THE DEVELOPMENT OF INTACT STABILITY CRITERIA FOR DISPLACEMENT VESSELS. (Cont'd.)

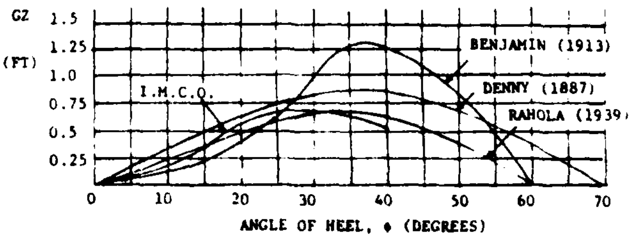
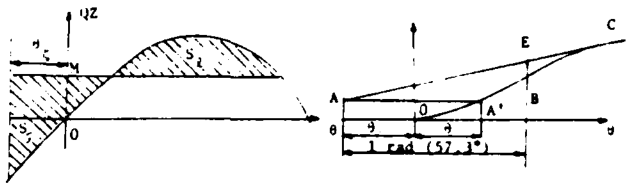
[illegible]	[illegible]	[illegible]	COMMENTS
[illegible]	[illegible]	[illegible] $\frac{PA\ell}{\Delta \tan \phi}$ = minimum $P = (\ldots) + (\frac{L}{14200})$ tons ft^2 for oceans, [illegible] and Great Lakes winter service $P = \frac{L}{1000} + (\frac{L}{14200})$ ton ft^2 for lakes, bays, sounds, and Great Lakes summer service. $P = \frac{L}{1000} + (\frac{L}{14200})$ ton/ft^2 for rivers, harbors and other protected water. L = length (L.B.P.), ft A = projected lateral area above waterline. ℓ = distance from center of A to half draft point, ft. Δ = displacement, L. tons. φ = heel angle to one-half freeboard or 14° whichever is less PASSENGER SHIPS $GM > \frac{Nb}{24\ \Delta \tan \phi}$ passenger N = number of passengers b = distance from ship ℄ to center of passenger deck on one side, ft. φ = angle of heel to deck edge or 14° whichever is less. OFFSHORE SUPPLY VESSELS $e_{40} \geq 15$ ft. deg. e_{40} = area under righting arm curve up to the lesser of 40°, the angle of max. righting arm, or the angle of down flooding.	United States Government Code of Federal Regulation Title 46 "Shipping", containing section 73.1 (SubChapter H) and Section 4.07 (Chapter I), is the weather criterion which the U.S. Coast Guard applies to all passenger and merchant ships. These codes employ the initial metacentric height and freeboard to assess the extent of stability. In addition other specialized stability criteria have been established covering drilling rigs, sailing vessels, deck cargo barges, tug boats, etc. In particular for Offshore supply Vessels, the U.S.C.G. adopted in 1964 a stability criterion similar to Raholas following the recognition that GM limits alone were insufficient.
1966	ILLC		The 1966 International Load-Line Convention, which came into effect in 1968 required all vessels over 79 ft. on international voyages to have their stability checked.
1968	Nadeinski		IMCO progress reviewed by Nadeinski and Jens. for fishing vessels. New recommendations differed little from Rahola's results.
1968	IMCO	a) GM ≥ 0.49 ft passenger ships GM ≥ 1.15 ft fishing vessels b) $\phi_m > 25°$ (ϕ_m is φ at max GZ) c) GZ > 0.66 ft at φ ≥ 30° d) Dynamical lever (e) $e_{30} \geq 10.3$ ft.deg; φ = 30° $e_{40} \geq 16.9$ ft.deg; φ = 40° or φ at the angle of flooding $e_{40} - e_{30} \geq 5.6$ ft. deg.	Intergovernmental Maritime Consultative Organization published intact stability standards for passenger and cargo ships. The IMCO recommendation for ships under 328 ft. was based on a sample statistical analysis of the righting-arm curves of capsized ships. The result is a standard very similar to that obtained by Rahola (1939) as illustrated in the figure below:  (From BIRD 75) Note that the effect of winds and waves are excluded and the results have been critized for inconsistencies in the statistical data base.

TABLE 3-1. SIGNIFICANT MILESTONES AND CONTRIBUTIONS IN THE DEVELOPMENT OF INTACT STABILITY CRITERIA FOR DISPLACEMENT VESSELS. (Cont'd.)

YEAR	PRINCIPAL INVESTIGATOR	RELEVANT FORMULA	COMMENTS
1971	Beukelman		Analytical and experimental study of the effect of forward speed on lateral stability of beam-trawlers in calm and rough water with head and following seas.
1971	USSR	$K = \frac{M_c}{M_v} \geq 1$ M_c = moment to capsize M_v = "dynamical" heeling moment = $0.001\ P_v A_v Z$ P_v = wind pressure given as a function of Z A_v = projected lateral area above waterline Z = height of area centroid above waterline	A conventional "dynamical" stability criterion (Moselev 1850) is used with the influence of rolling introduced via an empirically based calculation of the amplitude of rolling with this amplitude used as the initial angle of heel. The amplitude of rolling ϕ_r is expressed graphically as a function of ship beam, draft, block coefficient and initial G.M. 
1972	Paulling		Free-running cargo-ship model capsizing tests in heavy seas. Tests conducted in San Francisco Bay showed that capsizing occurred in one of three modes: (a) low-cycle resonance due to passage of several steep waves. (b) a single large wave causes loss of stability for a sufficiently long time to allow capsize. (c) broaching in steep breaking waves when rudder cannot hold course and dynamic effect of returning causes capsize.
1976	Odabasi	Two principal sets of equations must be satisfied which involve (a) stability against parametric resonance (small angles of roll) for a selected design-wave condition. (b) the determination of the maximum possible angle of roll which must lie within the region of stability or angle of down-flooding.	A very significant new intact-stability criteria is presented which is based on the theory of stability of motion. The advantage of the criteria is that capsizing can be predicted which cannot be predicted by existing standards. The criterion is applied to the prediction of capsizing of MT. Edith Tericol. Limitations of the new criterion are mentioned and the need for further research is emphasized.
1976	Amy	Specific standards are quoted to govern the heeling-arm curves for the following hazards: (a) Tripping of towing vessels in calm water (b) Water on deck in low-speed head or following sea operation. (c) Loss of stability in high-speed operations in following seas. (d) Rolling with wind heel and water on deck in beam-sea operations.	An experimental and analytical study of intact stability requirements for U.S. towing and fishing vessels is presented. The characteristics of the U.S. towing and fishing fleets in general were gathered, and 51 vessels were characterized in detail. Four models of representative vessels were built and tested in calm water and in regular waves. The calm-water tests studied towing vessels' tripping by their own power, and by the movement of their tow. The tests in waves took place in following, beam, and head waves, with the vessels running free or towing. The relationships between a vessel's power, handling, and proportions, and its probability of capsizing were studied. A set of stability criteria for use by the USCG was presented.
1979	Wright		A simple equation of roll motion (intended for beam-sea applications) is set up and three approximate methods of solution for the regular response are described. The simple equation allows the system to be biased, but modes of motion other than roll are suppressed. Additions to the simple roll equation are proposed which allow heave, pitch and sway to be included and also parametric excitation. Some progress towards the theoretical prediction of capsize in non-regular waves is also reported. Predictions based on the analysis of the simple roll equation are compared with the results of model experiments in a regular beam sea. Some sets of computed results are presented which illustrate the effect on the regular roll performance of varying the parameters of a hypothetical GZ curve which was chosen to be near the limits allowed by the present IMCO stability criteria. These results illustrate the important influence of the range of stability and roll damping on the safety of a ship from capsize.

3.2 STABILITY STANDARDS FOR HYDROFOIL CRAFT IN THE DYNAMICALLY SUPPORTED MODE

3.2.1 Craft with Surface-Piercing Foils

For hydrofoil craft with surface-piercing foils, no specific stability standards could be found from the literature search conducted as part of the background study. However, SUPRAMAR, in their report of DEC 76, provide some simple design guidelines and the IMCO Resolution, 14 NOV 77, identifies some general considerations. Methods similar to those presented by SUPRAMAR for assessing the stability of craft with surface-piercing foils can also be found in BATH IRON 54. Both the Supramar and Bath Iron Works reports are, however, only concerned with small angular motions about normal trim conditions in still water. The guidelines available are summarized as follows:

(a) IMCO 14 NOV 77

> Chapter 2.5 STABILITY OF THE CRAFT IN THE NON-DISPLACEMENT MODE
>
> 2.5.1 The Administration should be satisfied that, when operating in the non-displacement and transient modes within approved operational limitations, the craft will, after a disturbance causing roll, pitch, heave or any combination thereof, return to the original attitude.
>
> 2.5.2 The roll and pitch stability of each craft, in the non-displacement mode, should be determined experimentally prior to entering commercial service and be recorded.
>
> 2.5.3 Where craft are fitted with surface-piercing structure or appendages, precautions should be taken against dangerous attitudes or inclinations and loss of stability subsequent to a collision with a submerged or floating object.

> Appendix II, Chapter 1.2 STABILITY IN THE TRANSIENT AND FOIL-BORNE MODES
>
> 1.2.1 The stability should satisfy 2.5 of this Code.
>
> 1.2.2 (a) The stability in the transient and foil-borne modes should be checked for all cases of loading for the intended service of the craft.
>
> (b) The stability in the transient and foil-borne modes may be determined either by calculation or on the basis of data obtained from model experiments and should be verified by full-scale tests by the imposition of a series of known heeling moments by off-centre ballast weights, and by recording the heeling angles produced by these moments. When taken in the hull-borne, take-off, steady-foil-borne, and settling-to-hull-borne modes, these results will provide an indication of the values of the stability in the various situations of the craft during the transient condition.
>
> (c) The time to pass from the hull-borne to foil-borne mode and vice versa should be established. This period of time should not exceed two minutes.
>
> (d) The angle of heel in the foil-borne mode caused by the concentration of passengers at one side should not exceed 8°. During the transient mode the angle of heel due to the concentration of passengers on one side should not exceed 12°. The concentration of passengers should be determined by the Administration, having regard to the guidance given at Appendix III to this Code.

Appendix III, PASSENGER LOADING

1. A mass of 75 kilogrammes should be assumed per passenger except that this value may be reduced to not less than 60 kilogrammes where this can be justified. In addition, the mass and distribution of the luggage should be to the satisfaction of the Administration.

2. The height of the centre of gravity for passengers should be assumed equal to:
(a) 1 metre above deck level for passengers standing upright. Account may be taken, if necessary, of camber and sheer of deck.

(b) 300 millimetres above the seat in respect of seated passengers.

3. Passengers and luggage should be considered to be in the space normally at their disposal.

4. Passengers should be considered as distributed to produce the most unfavourable combination of passenger heeling moment and/or initial metacentric height which may be obtained in practice. In this connexion, it is anticipated that a value higher than four persons per square metre will not be necessary.

(b) SUPRAMAR DEC 76

In this report a comprehensive description is given of the development of the Supramar series of hydrofoil craft, which were, until recently, exclusively of surface-piercing foil types. The primary point of interest, therefore, is the insight provided to the design of such craft.

The influence of stability requirements on the principal features of foil design is discussed and empirical rules are given to assure adequate initial stability. The range of stability is not considered nor are criteria given for maximum righting moments.

A point is made of the seakeeping ability of the surface piercing foil system whereby, at reduced speed, additional foil area is immersed and damping is enhanced. However, the foil tip becomes immersed at a smaller heel angle and the foil span-loading is reduced by the speed reduction and it is not clear that maximum transverse righting moment is improved.

The considerations given to transverse, longitudinal and directional stability are as follows: -

- Transverse Stability

The relationship between transverse stability and foil geometry is illustrated for a typical foil system in Figure 3-1. With a heel angle ϕ applied to a single foil, its lift is shifted towards the more deeply immersed side. The lift vector L_F is then applied through the point G' and intersects the craft's centerline at the metacenter M. The measure of transverse stability of the single foil, as with conventional, displacement-ship terminology, is then the metacentric height, as given by:

$$GM = h - (a + g) = h - s \qquad (1)$$

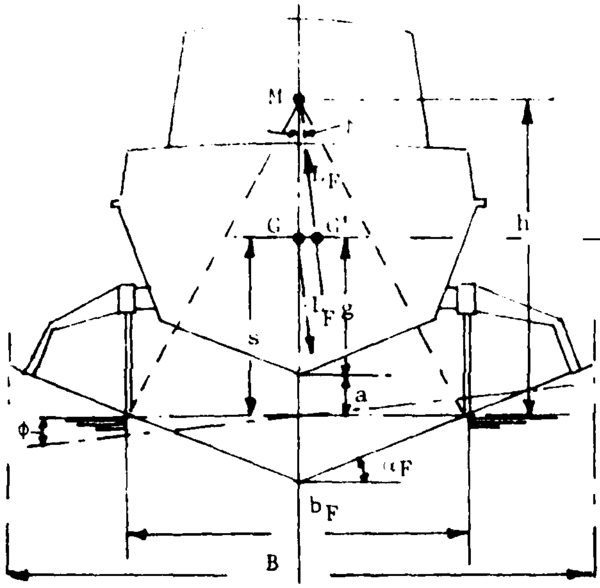


FIGURE 3-1. SECTION THROUGH FRONT FOIL.

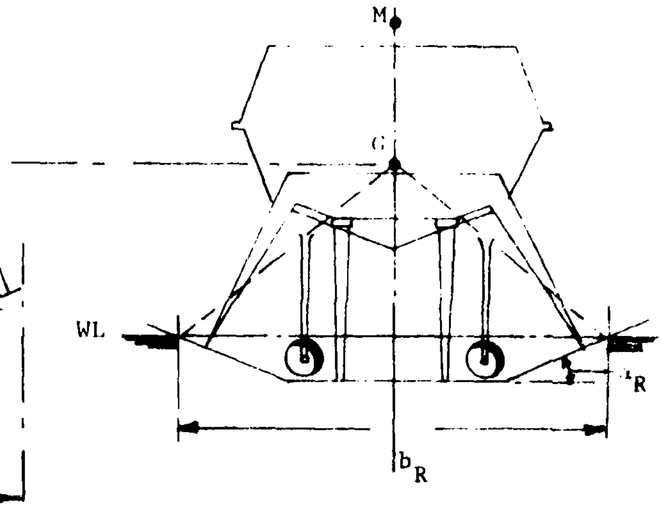


FIGURE 3-2. SECTION THROUGH REAR FOIL.

where h = $1/2\, b_F \cot .\ \alpha_F$ (2)

a = keel flying height above water

g = c.g. height above keel

b_F = wetted span of foil plan view area

α_F = dihedral angle

since GM_F = h - s (see Figure 3-1)

$\therefore$ $GM_F = 1/2\ b_F \cot\ \alpha_F - (a + g)$ (3)

The wider the wetted span of the foil and the smaller the dihedral angle α_F, the higher the transverse stability of the V-shaped foil becomes. This derivation of GM is for a single V-shaped foil having essentially rectangular lift distribution. For non-uniform lift distribution a correction factor must be applied. (SUPRAMAR DEC 76)

With foils in tandem, the forward and aft foils (see Figures 3-1 & 3-2) act in combination to give

$$GM_T = (GM_F\ L_F + GM_R\ L_R)\ 1/\Delta \tag{4}$$

where $\Delta = L_F + L_R$ = craft displacement

L_F = lift from forward foil

L_R = lift from rear foil

with η_F = load factor of forward foil = L_F/Δ

η_R = load factor of rear foil = L_R/Δ

$$GM_T = \eta_F\ [\ 1/2\ b_F \cot\ \alpha_F - s] + \eta_R\ [1/2\ b_R \cot\ \alpha_R - s\ ] \tag{5}$$

$$= \eta_F\ (\ h_F - s) + \eta_R\ (h_R\ - s)$$

and the righting moment becomes

$$M = \Delta \; GM_T \; \sin \phi \tag{6}$$

Based on SUPRAMAR experience (SUPRAMAR DEC 76) adequate transverse stability is obtained when

$$\left(\frac{h}{s}\right)_{total} \geq 1.9 \tag{7}$$

The term (h/s) contains the flying height (a) which can be freely chosen during design. The flying height (a) also determines, to a great extent, the span of the foil, and is governed by seakeeping requirements. In SUPRAMAR DEC 76, the following, state-of-the-art guidelines are given:

$$a = 0.2 \;\; \Delta^{1/3} \text{ for non-stabilized foils}$$
$$a = 0.3 \;\; \Delta^{1/3} \text{ for stabilized foils} \tag{8}$$

Also, since from combining equations (1) and (5)

$$\left(\frac{h}{s}\right)_{total} = \frac{\eta_F h_F + \eta_R h_R}{s} \tag{9}$$

Therefore from equation (7):

$$\left(\frac{h}{s}\right)_{total} = \eta_f \left[\left(\frac{b_F}{2s}\right) \cot \alpha_F\right] + \eta_R \left[\left(\frac{b_R}{2s}\right) \cot \alpha_F\right] \geq 1.9 \tag{10}$$

Also, for vessels with fully submerged rear foils.

$$\left(\frac{h}{s}\right)_{total} = \left(\frac{\eta_F \; b_F}{2s}\right) \cot \alpha_F + \eta_R \geq 1.9$$

- <u>Longitudinal Stability</u>

A detailed (but simple) formula for the computation of the longitudinal metacentric height (GM_L) available from the combination of fore and aft foils is given in SUPRAMAR DEC 76.

Their recommendation is that the nondimensional metacentric height (GM_L/L_T) should lie between 3.5 and 5.5 where L_T is the longitudinal distance between foils.

- <u>Directional Stability</u>

SUPRAMAR DEC 76 also gives some general guidance for adequate directional stability. A method for calculating the transverse forces on aft and forward foils is given along with a derivation of the moment balance about a vertical axis through the craft's c.g. It is recommended that the yawing moment contribution of the aft foils must be at least 20% greater than the moment contribution of the forward foils for adequate directional stability.

3.2.2 Craft with Fully Submerged Foils

The dominant motivation for the use of fully submerged hydrofoils has been the alleviation of seaway disturbances and the resulting achievement of extremely good ride quality in what are, for small craft, very severe seas. Thus, a great deal of the design and development effort (largely carried out by the U.S. Navy and its contractors) has been directed to this end. The U.S. Navy's latest hydrofoil dynamics specifications and criteria, as formulated in BOEING MAR 77, and much of the background literature have been reviewed.

This two-volume study represents a distillation of the Boeing Company's twenty years of experience in the design and testing of hydrofoils. The format is a proposed U.S. Navy specification of stability and control features of submerged-hydrofoil ships as well as the analysis and test procedures to be applied for verification of compliance.

The specifications presuppose the establishment of a design maximum sea state and place a good deal of emphasis on ride quality. The adequacy of control authority is addressed, however, and corresponding criteria are set forth. Avoidance of cavitation on foils and flaps is emphasized.

Since the foilborne stability of submerged-hydrofoil ships depends on both mechanical and electrical components of the automatic-control system, as well as on the geometry and structure of the strut-foil system, the analysis of control-system failure is discussed in depth. The importance of control-system reliability is emphasized and means for its assurance are discussed.

This study is still in preliminary form and subject to review by the Navy and other Navy contractors. In its final form it should provide the most authoritative base for the development of U.S.C.G. stability standards.

The specifications given, however, appear to go beyond what are required from considerations of safety. The following discussion represents an attempt to extract those criteria which are strictly related to intact stability. Other important, safety-related considerations such as failure analysis and maneuverability and collision avoidance are not addressed.

The stability and, ultimately, the safety of a craft with fully submerged hydrofoils depends on the hull, on the strut and foil system (including moveable control surfaces), and on the essential automatic-control system (ACS) for manipulation of the moveable controls. The capabilities and limitations of each must be integrated in the design to provide adequate maneuverability and seakeeping with acceptably low risk of casualty.

General Requirements

Several sources of hazard must be recognized. For example, the stability of the craft may be adversely affected by the loading of the craft. Thus, the stability should be investigated for all reasonable variations of loading and, if necessary, bounds should be established for the amount and distribution of loads. Any such restrictions must, of course, be known to the operator.

The running trim of the craft in height, pitch, roll and control surface deflection will affect the stability. This is governed by the ACS but is subject to variations of loading and, to some extent, to adjustment by the operator. Thus, for example, a height adjustment is usually provided as may also be a pitch-trim adjustment. Any adverse effects of extreme trim adjustments must be known to the pilot.

In addition to trim adjustments the controls available to the pilot may include a selection of ACS mode for takeoff, for example, or for rough-water operation. If selection of an inappropriate mode can lead to a stability hazard, adequate warning must be given to the pilot.

Most hydrofoil craft can safely perform any maneuver which the pilot can order by his helm and throttle controls. The pilot must be made aware of any exceptions which cannot be eliminated by design.

In general, a craft with fully submerged hydrofoils can negotiate seas when foilborne, provided that the wave heights do not exceed the limits imposed by her size and strut length. Even the largest contemplated craft will be unable to fly in the most severe north Atlantic storm. Thus, any craft will be designed to provide a required level of ride quality and maneuverability in a specified sea state. It is anticipated that a craft will not put to sea when conditions are expected to exceed her design sea state. Nevertheless, the reliability of sea-state prediction is not adequate to preclude encountering more severe conditions. Experience has indicated that, for some severe seas, it will be impossible to maintain flying speed. The craft must then take refuge in hullborne operation. Safe operation up to this limit sea-state must be assured. Otherwise a sea-state meter, or its equivalent, must be provided to warn the pilot of unsafe conditions.

Other environmental influences besides sea waves may be important, including wind and ice accretion. Proper account of these influences must be taken.

Since the stability of craft with fully submerged hydrofoils depends on the proper functioning of an extensive and complicated mechanical and electrical system, the possibility of failure must be addressed. This is done in two ways,

1. By careful design, including provision for redundancy of critical elements, and the selection of the most reliable available components to reduce the probability of failure to an acceptable level.

2. To attempt to assure that the results of any single failure will not be catastrophic. This requires an analysis of the effects of hypothetical failures and may also justify simulated failure tests in full scale.

Stability Criteria

A. TRIM

Foilborne trim refers to the pitch angle, roll angle and control-surface deflections prevailing in steady, straight, calm-water flight at a set height. It is determined by the action of the automatic control system (ACS) and is affected by the design of the strut/foil system as well as that of the ACS and by the loading of the craft. In addition it varies with the speed.

What is important from the stability point of view is that a sufficient range of control forces be available, beyond the trim deflections, to counter environmental disturbances. In addition the pitch attitude, in particular, must not be such as to prejudice the directional stability or unduly increase the likelihood of foil broaching. The trim must be examined with these points in mind and, if necessary, limits on loading, height and foilborne speed established.

Figure 3-3 illustrates the relations between craft speed, pitch and after flap trim angles for a hypothetical craft. If a linear control law is used to relate the flap deflection to the pitch variation from zero, then the trim condition will be along the appropriate (dotted) gain line. A gain of 1 would appear to produce excessive pitch angle, whereas a gain of 2 results in rather large flap deflections. Thus, a gain of about 1-1/2 may be near optimum.

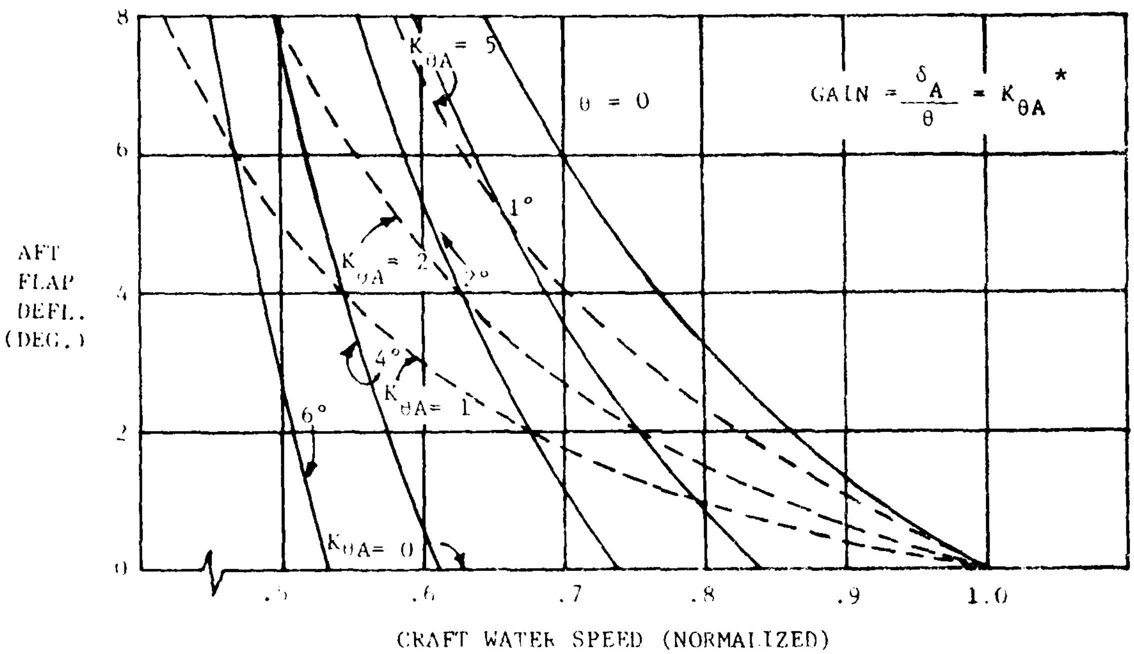


FIGURE 3-3. STEADY-STATE TRIM PROFILES FOR VARIOUS CONTROL GAINS. (derived from BOEING MAR 77)

Adjustment of the height is usually available to the pilot and adjustment of the pitch trim may also be provided. The pilot is then responsible for maintaining suitable trim for the prevailing sea conditions.

---

* δ_A is the deflection of the control flaps on the after foil.

θ is the pitch angle variation from desired level trim.

$K_{\theta A}$ is the factor by which θ is multiplied to obtain the equilibrium δ_A.

B. SPEED

Because of the characteristic shape of the drag versus speed curve for a hydrofoil craft, with a hump approximately at the takeoff speed and a minimum at a slightly higher speed, there is a speed interval within which steady speed cannot be maintained at constant throttle setting. A potential hazard exists in heavy seas, which cause speed fluctuations, that the speed may drop into this unstable region with a resultant further loss of speed and concomitant loss of roll control authority. The pilot should be warned to maintain adequate speed in extreme seas. In addition, when elevon controls are employed, the ACS should be designed to avoid full flap deflection, due to a pitch error, which could exhaust the roll control.

C. PITCH & HEAVE (HEIGHT)

Motions in pitch and heave are so intimately coupled that it is essential they be treated together. Variation of the height of the hull above the water, or the equivalent foil submergence, is the result of normal velocity and pitch-angle excursions. Thus, it is possible to eliminate the normal velocity from the dynamical equations and substitute the height and its derivatives. In fact, this is essential since the height can be measured and is a variable subject to control along with the pitch angle.

Two modes of motion will be present, one perhaps predominantly in heave, the other in pitch. Because of the pitch/heave coupling, however, both modes will provide pitch and height excursions. Both modes must be adequately stable. Design criteria in the form of gain and phase margins can be applied. Verification can be accomplished during calm-water foilborne trials by making rapid (step) changes in the height and pitch commands.

The design of the ACS is usually such that the forward-foil deflection is determined by height error, modulated by the vertical acceleration, while the after foil is mostly responsive to pitch-angle error. Conversely, the height is controlled by the forward foil and pitch by the after foil. Loss of adequate speed leads inevitably to loss of support and a retreat to hullborne operation. The distribution of load and the design of the foils and the ACS must be such as to insure pitch control at all speeds at which flight can be maintained. Care must also be taken to insure that the incidence of cavitation cannot reduce the available control force below a safe level at any speed.

D. YAW

Generally speaking it is possible to achieve course stability, in the sense that a yaw-rate disturbance will decay if the rudder is precisely centered, without the provision of static stability in yaw - sometimes referred to as weathercock stability. On the other hand, if static yaw stability is provided, then course stability is almost certain to result. Thus, it is usual to require static yaw stability, about the center of gravity, with the rudder fixed.

Yaw stability depends on the distribution of strut area and can also be influenced by foil dihedral. The effective strut-area distribution is affected by the flying height and more especially by the pitch trim. The stability is adversely affected by ventilation of the after struts. Thus, the criterion has been proposed by the Boeing Company that the pitch trim must always be more positive (bow up), at any speed, than that required to assure yaw stability with the after strut(s) ventilated. Furthermore, stability must be obtained with the pitch trim 2° more negative when all struts are fully wetted. Figure 3-4 shows the stability boundaries for a hypothetical ship in terms of strut immersion with all struts fully wetted and also with the after struts ventilated. A suggested minimum-pitch trim line is also shown.

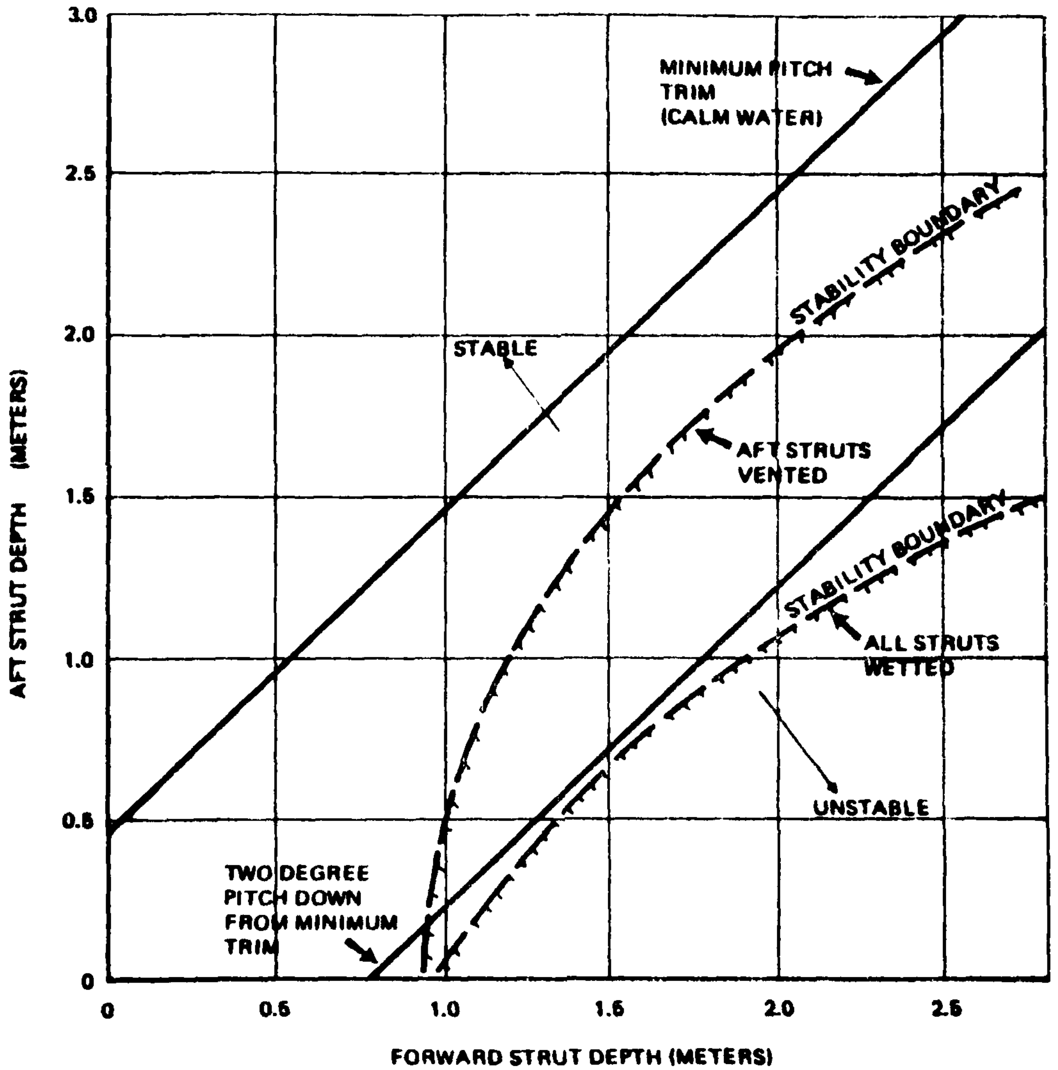


FIGURE 3-4. TYPICAL DIRECTIONAL STABILITY BOUNDARIES. (BOEING MAR 77)

The latest U.S. Navy hydrofoil ships have been fitted with a feature called bank to turn. With this arrangement of the control system the helm produces a roll command, or what could,perhaps more properly,be termed a roll trim. Response of the craft in roll is sensed by a gyro and this signal is used to direct a deflection of the rudder to turn the craft in the direction of the roll. Thus the craft is always banked into a turn. By the same token the rudder responds to any roll disturbance so that course stability is coupled to roll stability. The resulting steering is excellent. Furthermore, if a large roll angle develops through any failure of roll control, the craft is turned toward the roll which tends to alleviate its seriousness.

E. ROLL

As with most ships and other marine vehicles the roll mode constitutes the most critical aspect of stability because the potential for catastrophe is greatest. The craft with fully submerged foils depends almost entirely on active controls for roll stability; the inherent stability due to the effect of differential surface proximity is trivial by comparison. On the other hand the available righting moment is usually so large at normal foilborne speeds that wind loads and off-center passenger loads are negligible. In particular, the present practice of using banked turns renders trivial any heeling moment in a turn. Only at the lowest foilborne speed, or when forced below minimum flight speed, are such disturbances considerable. The mode of escape in such an event is to ditch the craft, which can be done quickly by cutting the throttle and reducing the height command. Potential difficulty at takeoff can be avoided by choice of suitable course with respect to wind and sea directions.

The most important source of roll disturbance is the water velocity due to the orbital motion in waves. In beam seas the horizontal component of the orbital velocity produces side slip and resultant side forces on the struts while the vertical component alters the angle of attack, and hence the lift, on the foils. This is illustrated in Figure 3-5 which shows a craft poised on a beam wave of height equal to the strut length, a 7:1 length to height ratio, and with the crest at one of the side struts. An alternative scenario, shown in Figure 3-6, puts the crest of a 7:1 wave of length equal to the foil span amidships. The Boeing Company has proposed,as a criterion of roll-control authority,that at any foilborne speed, the righting moment obtainable from deflection of the ailerons (and the rudder,if roll-to-steer control is provided) must be larger than the heeling moment produced by either of the above beam-sea conditions. The example in Figure 3-7 shows the results of such a calculation for a hypothetical craft.

In order to maintain roll control at as low a speed as possible, the ACS must be designed so that the ailerons (elevons) cannot be saturated as a result of height or pitch errors.

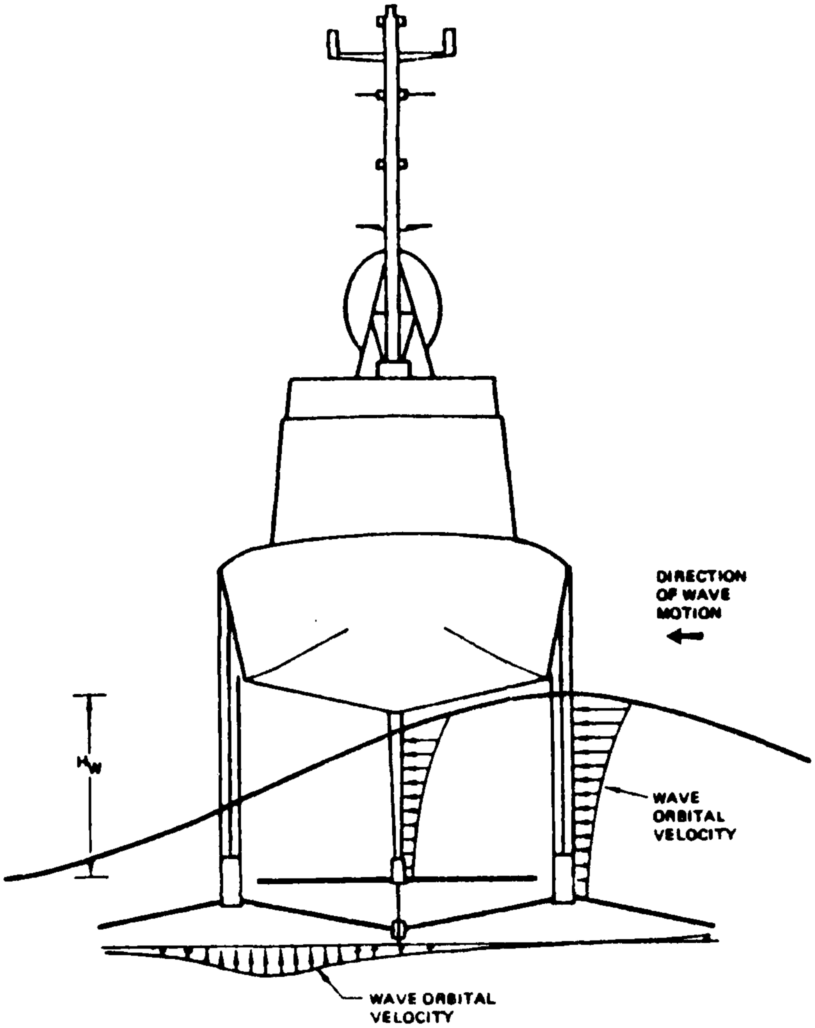


FIGURE 3-5. DISTURBANCE FORCES FROM DESIGN WAVE NO. 1. (BOEING MAR 77)

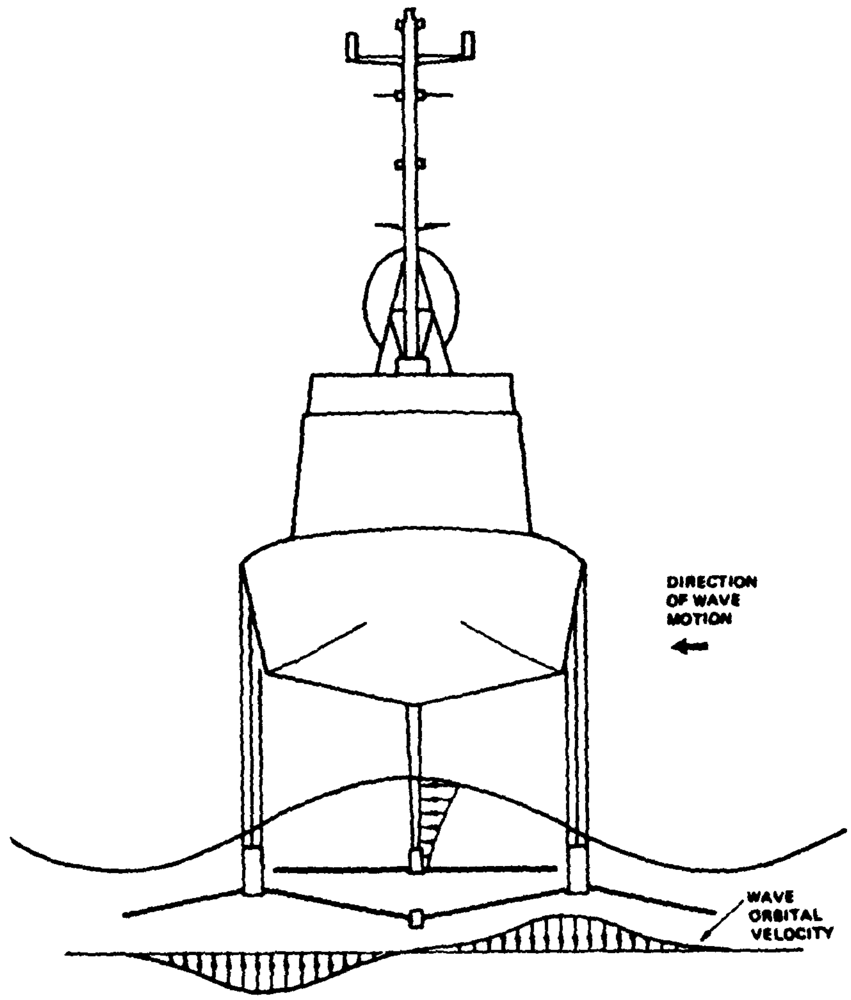


FIGURE 3-6. DISTURBANCE FORCES FROM DESIGN WAVE NO. 2. (BOEING MAR 77)

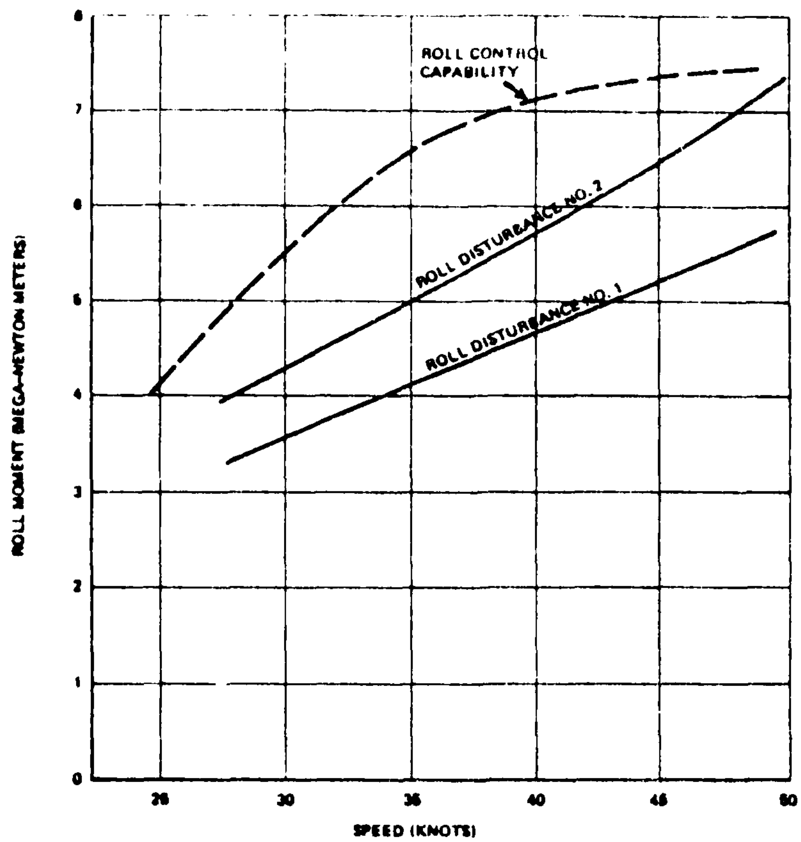


FIGURE 3-7. ROLL-CONTROL AUTHORITY. (BOEING MAR 77)

Experience with other types of vehicles indicates that the designer should be aware of the hazards due to broaching, due to loss of directional stability and due to the development of uncontrollable rolling moment. This did happen to the experimental, high-speed hydrofoil FRESH-1 as a result of improper height setting, pitch trim and perhaps foil-incidence setting as well. It is not known to have occurred on any later craft. It is believed that the employment of the roll-to-steer feature may be crucial in avoiding excessive side slip and the resulting rolling moment. Formulation of a stronger criterion than those discussed here would appear to require further study.

3.3 STABILITY STANDARDS FOR RIGID-SIDEHULL SURFACE-EFFECT SHIPS OPERATING IN THE DYNAMICALLY SUPPORTED MODE.

There are no widely recognized stability standards for the rigid-sidehull SES when operating in the dynamically supported mode. Since the early design investigations in the late 50's the provision for adequate stability has been almost exclusively assessed from the results of model testing. Some attempts have been made, however, to establish general design guidelines for safe operation under various hazards and these are discussed below:

3.3.1 Early U.S., SES General Requirements

(a) Static Stability (On-Cushion)

The ship shall be directionally stable in yaw over the entire range of pitch, sideslip and roll angles which the ship can assume while maneuvering in calm water and shall have the following static stability characteristics over the entire speed range: -

- (i) Positive righting moment in roll up to an angle of $\pm$ 6 degrees.
- (ii) Positive righting moment in pitch up to an angle of $\pm$ 3 degrees.

(b) Dynamic Stability (On-Cushion)

Roll, pitch and heave oscillations of the ship, when occuring, shall be damped to small values in several cycles. Particular concern shall be paid to the interaction of roll, pitch and yaw motions so that,at high speeds and in waves, the ship will not be placed into jeopardy of capsizing or plowing-in under worst-case combinations of attitude, wave location and control action.

(c) System Failures

The ship shall be designed to operate safely in the event of any of the following malfunctions or failures, regardless of the sea state and speed at the time of the failure: -

- (i) Failure of any combination of propulsors.
- (ii) Lift-system failure.
- (iii) Bow-seal failure.
- (iv) Stern-seal failure.
- (v) Failure of any nonredundant control device.

(d) Stability Off-Cushion

The ship shall have sufficient stability, structural strength and reserve buoyancy while off-cushion to withstand

- (ii) A 100-knot beam wind combined with rolling
- (iii) A side-shell plating opening, of length equal to 15 percent of the overall length of hard structure, at any point fore and aft along the sidehull, together with a 30-knot beam wind with rolling.

Although the present study is concerned only with intact stability, damage or system failure considerations have been included above since these can often dictate overall stability requirements.

3.3.2 AGC Craft Dynamics Program 1969

During the late 60's Aerojet General Corporation (AGC), under U.S. Navy sponsorship, performed a very extensive craft-dynamics investigation with the U.S. Navy's XR-3 test craft as the principal subject. The investigation pursued two main objectives; the development of the equations of motion and subsequent stability-and-control analysis of the craft, and the development of the equations of motion of the bow-and stern-seal systems and their force contributions to the whole craft. These analytical developments were conducted parallel with supporting model-test programs. Data from the test programs were used to update or modify the equations and their coefficients. Predicted performance based on the modified equations was then compared with model-and full-scale XR-3 test results. As a result of this study, safe operational envelopes for the XR-3 were established and specific stability criteria were recommended for future designs. Pertinent results of the study are summarized below:

(a) Stability Against Rolling Over in Extreme Conditions

The possibility of rolling over in the presence of large side forces acting on the sidehulls is the main consideration with regard to the safety of an SES. To operate at high speed in the on-cushion mode, the sidehull depth of immersion must be kept small, and, for effective operation in waves, a reasonably large clearance must be allowed between the wet deck and the bottom of the sidehulls. Design restrictions generally require that the c.g. be somewhat above the wet deck. Hence, the craft normally rides with its c.g. relatively high above the water surface, so that the forces acting on the sidehulls can have relatively large roll moment arms and can produce large overturning moments.

In practice, when an SES rolls in response to an overturning roll moment, the up-going sidehull does not rise appreciably above the water surface. If it rose further, a large air leakage area would appear under the sidehull, resulting in a drop in cushion pressure. Consequently, the craft's heave position would be reduced, under the action of the craft's weight, until the leakage gap is effectively closed. This would restore the sidehull to the water surface.

With the up-going sidehull assumed to remain at the water surface, the rolling of the craft will result in a greater immersion of the down-going sidehull, and, in the presence of a given side velocity, the side force acting on the sidehull and the associated overturning moment will increase as the roll angle increases, and this destabilizing effect becomes stronger as the magnitude of the side velocity increases. The hydrodynamic sideforce Y_D could, for a first approximation, be equated to the lateral acceleration due to turning.

ie $$Y_D = \frac{WU^2}{gR}$$ (see Figure 3-8b)

where W = craft weight

U = craft speed in the turn

g = acceleration due to gravity

R = radius of turn

In the presence of a sufficiently large side velocity, the destabilizing moment could overcome the maximum available restoring moment and the craft would overturn. The main objective, therefore, is to evaluate, as a function of the craft's design parameters, the magnitudes of sideslip angle that can be tolerated. Such an evaluation should be based for the most part on conservative assumptions. Hence, the values obtained would be understood to define safe operating limits rather than ultimate limits of stability.

The absolute limit of roll stability is defined by the roll angle beyond which the craft would roll over because the metacenter is below the c.g. For conservatism in the AGC study, a small, safe limit of roll angle was taken to be that angle causing the wet deck to reach the water surface. Such immersion could be produced by extreme conditions of side force acting on the sidehulls. The safe operating limits determined by this roll-over criterion are given for ranges of values of such parameters as length/beam ratio, pressure/length ratio, bubble-height/beam ratio, and c.g. height/beam ratio. The beam width is very important in determining stability against roll-over; a length/beam ratio less than 5.5 is necessary to limit the roll angle so that the craft's wet deck will not be immersed. For the nominal XR-3 length/beam ratio of 2.0, the vehicle was stable against rolling over for the expected extremes of c.g. height/bubble height ratio.

Although no hydrodynamic stabilizers, specifically designed for this purpose, are provided in the XR-3 design, the stern seal does provide a significant hydrostatic roll-restoring moment. This contriubtion was not included in the AGC MAY 69 study. Thus, the study may be taken to pertain to the case of a design that is stabilized solely by the hydrostatic restoring moment of the sidehulls. Alternatively, the study can be viewed as defining the stable operating limits, considering the remote possibility that the stabilizing contribution of the stern seal was lost through damage or failure. In application to the XR-3, the results obtained were, therefore, very conservative.

In addition to the destabilizing moment due to the hydrodynamic side forces acting on the sidehulls, a destabilizing moment generally of much smaller magnitude is contributed by the cushion aerostatic lift forces. This results from the lateral shift of the line of action of the cushion lift with roll angle. Although at higher speeds there is reason to believe that the destabilizing cushion lift moment will be compensated by lateral hydrostatic forces on the sidehulls, for conservatism no benefit was assumed from this effect, i.e., the destabilizing cushion lift moment was retained at all speeds.

Depending on design factors and turning conditions, the moment due to the forces acting on the rudders may be in either direction, i.e.,either tending to increase or decrease the roll angle. In any event,this moment is under the operator's control and presumably could, and would, be employed insofar as possible to counter conditions leading to excessive roll angles. Therefore, if the craft is otherwise stable and controllable, the rudder moment need not directly cause overturning. No rudder roll moment was included in the study although the rolling moment due to the rudder could be capsizing when pulling out of a turn.

In accordance with the foregoing comments, the contributions to the roll moment considered were: (1) the hydrostatic restoring moment, K_{HYS}; (2) the cushion lift moment K_L; and (3) the moment due to the hydrodynamic side forces on the sidehull, K_D. To maintain stability, the restoring moment, i.e., the first contribution, must increase more rapidly with increasing roll angle than the overturning moment, i.e., the sum of the latter two contributions.

When consideration is restricted to near-zero roll angles, the variation of each of the moment contributions with roll angle can be taken to be linear. Stability then depends upon whether or not the slope of the restoring moment exceeds the slope of the sum of the overturning moments; if so, the craft is stable at zero roll angle (with zero sidehull immersion); if not, the craft is unstable at zero-roll angle. However, in the latter case, stability may be reached at a non-zero roll angle, provided that, as the roll angle increases, the nonlinear increase in the restoring moment exceeds the nonlinear increase in the overturning moment. When the side velocity is reasonably small, the craft then comes to a stable equilibrium at a small roll angle with the down-going sidehull partly immersed as indicated in Figure 3-8a.

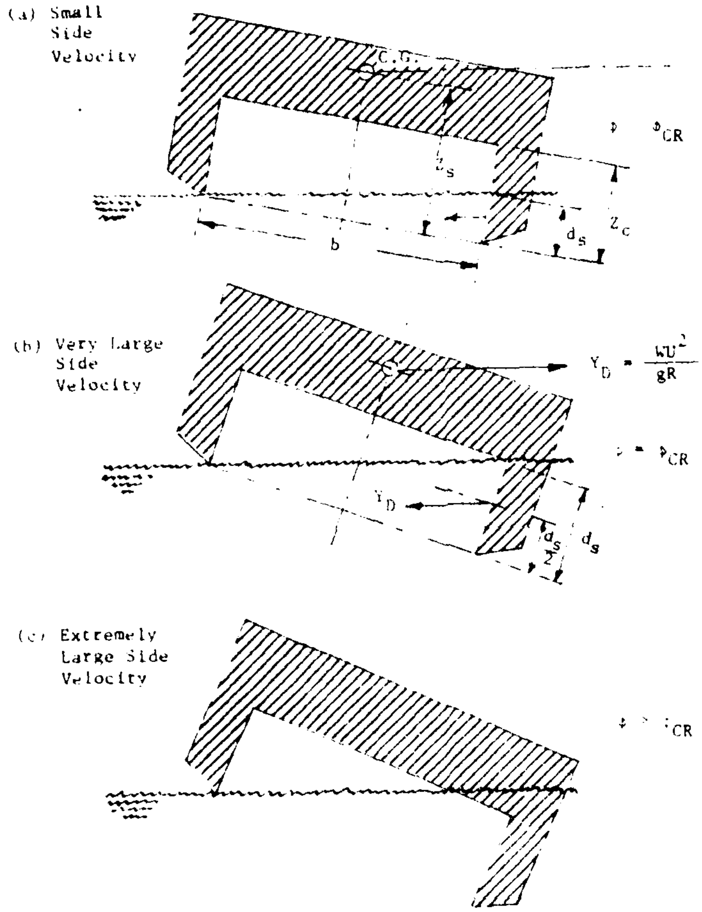


FIGURE 3-8. QUALITATIVE EFFECTS OF SIDE VELOCITY ON EQUILIBRIUM ROLL ANGLE, ϕ. (AGC MAY 69)

As the side velocity is increased the equilibrium roll angle increases and the immersion of the down-going sidehull increases. Eventually a point is reached where the sidehull is completely immersed and the yet deck touches the water on the down-going side, as illustrated in Figure 3-8b. The roll angle at which this condition is encountered is given by:

$$\phi_{CR} = \tan^{-1}\left(\frac{z_C}{b}\right)$$

where z_C is the cushion-height, i.e., the distance from the wet deck to the bottom of the sidehull, and b is the beam of the craft.

Generally, at the point where ϕ_{CR} is reached, the hydrostatic lift of the sidehulls will still have a large roll moment arm. Hence, after this point is passed and the wet deck becomes increasingly immersed, as illustrated in Figure 3-8c, the restoring moment will increase at a much greater rate. However, eventually a point would be reached where, because of the reducing roll moment arm and/or saturation of the available free-board, the restoring moment no longer increases as fast as the overturning moment increases. This point would define the extreme limit of roll stability.

Because of the complexities that are then involved in representing the hydrodynamic upsetting moment as well as the restoring moment, it is difficult to treat conditions obtained at roll angles beyond ϕ_{CR} on a generalized analytical basis. For AGC analysis, the point at which the roll angle reaches ϕ_{CR}, i.e., where the wet deck begins to become immersed, was taken as the limiting condition. The envelopes that define this limiting condition will invariably fall short of the ultimate limits of stable operation. Hence, these envelopes represent a very conservative bound for the limits of stable operation.

The variation of ϕ_{CR} with the cushion-height/beam ratio, z_C/b, is shown in Figure 3-9. For the XR-3, z_C is about 22 inches and b is about 10 ft. Hence, z_C/b is about 0.183 and ϕ_{CR} is about 10.4°. ϕ_{CR} for other craft are also shown on Figure 3-9.

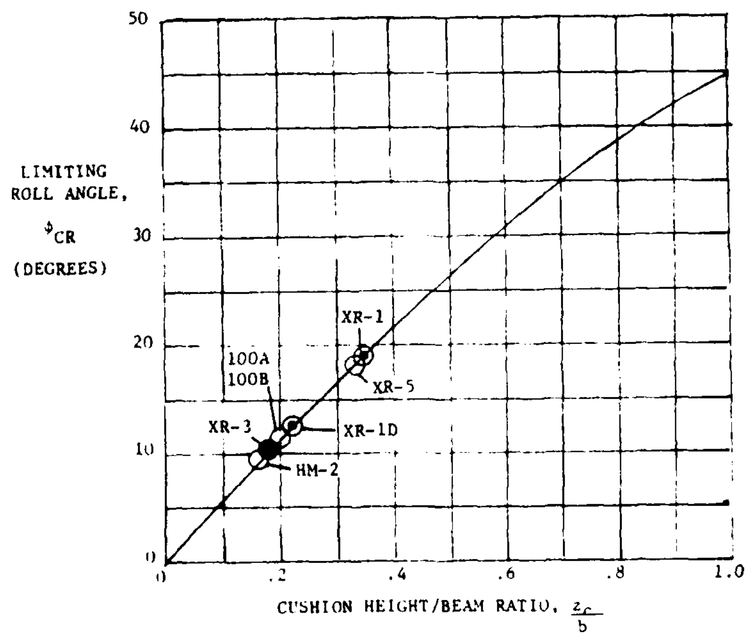


FIGURE 3-9. VARIATION OF LIMITING ROLL ANGLE WITH CUSHION HEIGHT/BEAM RATIO (AT $\phi = \phi_{CR}$ THE WET DECK BEGINS TO BE IMMERSED).

The net roll restoring moment is equal to the sum of three contributions, i.e.

$$K_{NET} = K_{HYS} + K_L + K_D$$

where K_{HYS} = Sidehull hydrostatic restoring moment (Figure 3-10)

K_L = Cushion aerostatic lift moment (Figure 3-11)

K_D = Sidehull moment due to hydrodynamic sideforce (Figure 3-12)

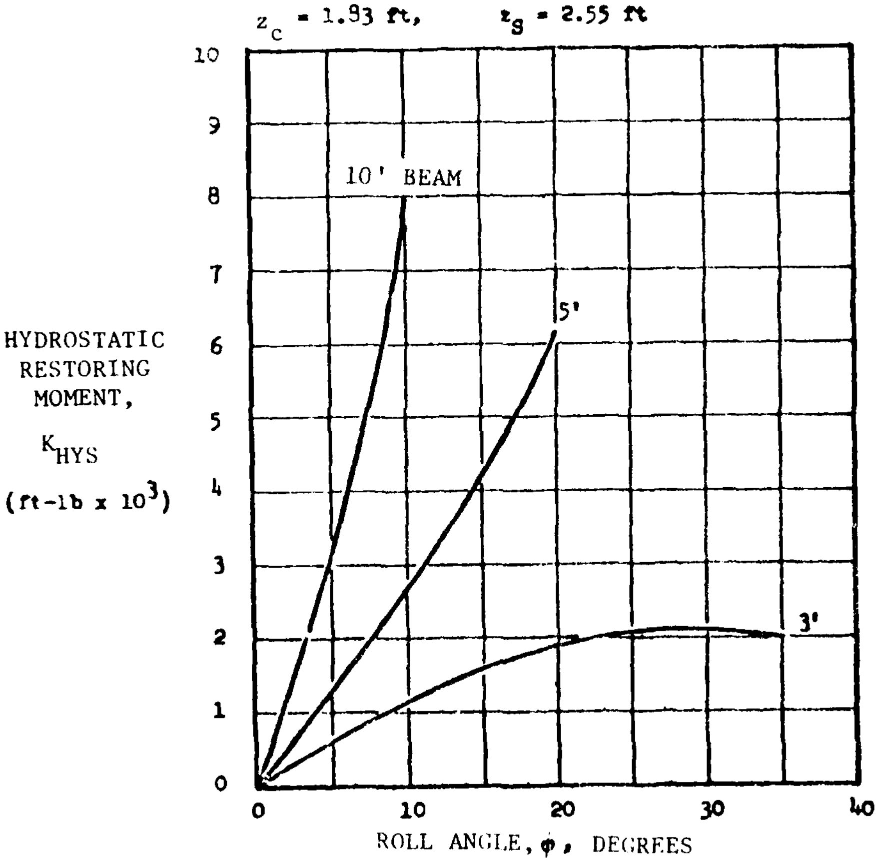
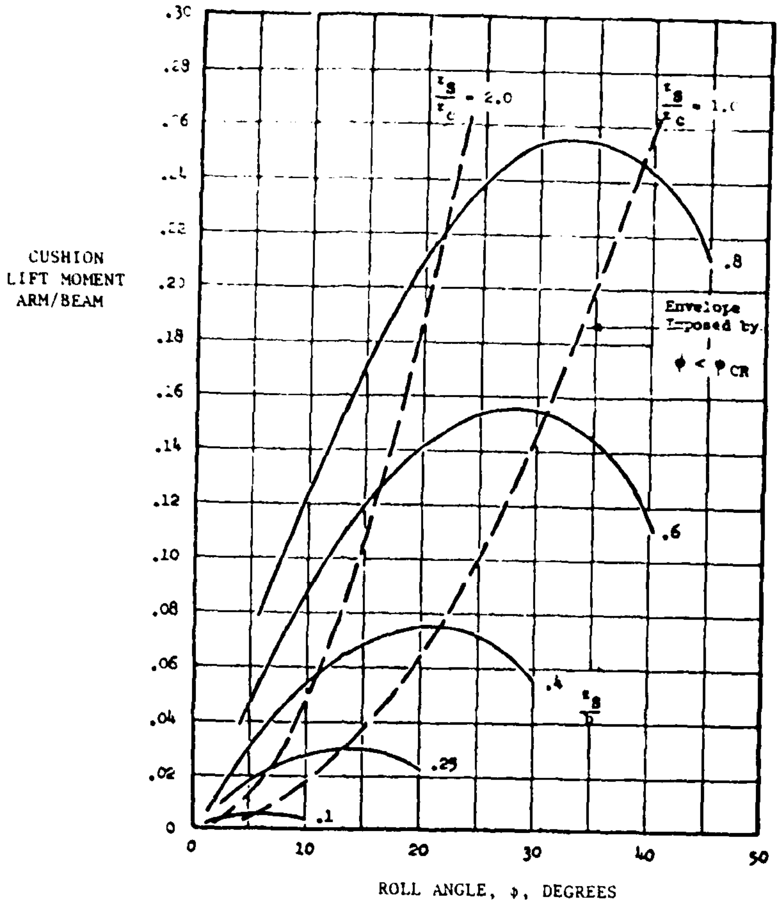


Figure 3-10. EFFECT OF REDUCTION IN BEAM ON VARIATION OF RESTORING HYDROSTATIC ROLLING MOMENT WITH ROLL ANGLE. (AGC MAY 69)



* z_s is height to C.G. from sidehull keel plane.

FIGURE 3-11. VARIATION OF BUBBLE LIFT MOMENT ARM WITH ROLL ANGLE, FOR VARIOUS C.G. HEIGHT/BEAM RATIOS. (AGC MAY 69)

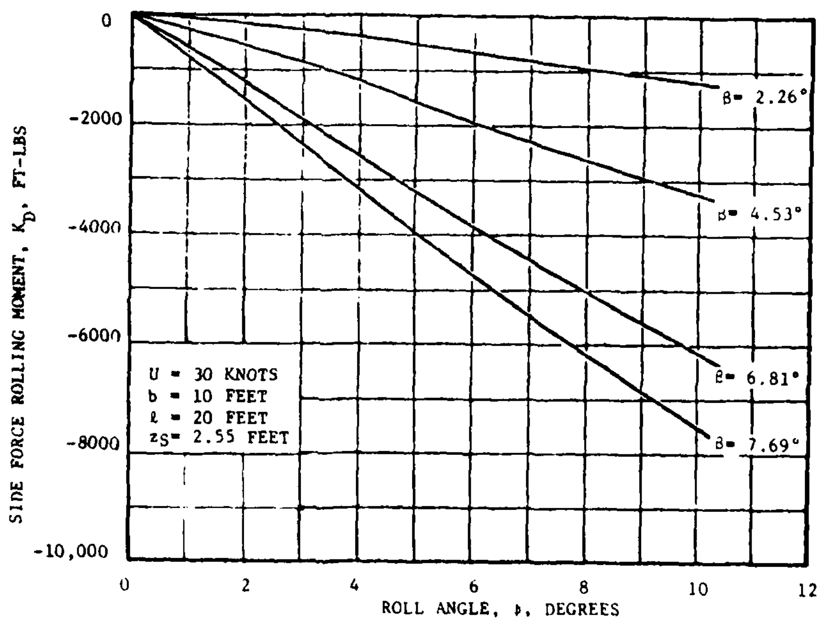


FIGURE 3-12. VARIATION OF SIDE MOMENT WITH ROLL ANGLE, U = 30 KNOTS, FOR VARIOUS β, NOMINAL XR-3 PARAMETERS. (AGC MAY 69)

An equilibrium is reached when $K_{NET} = 0$, and the equilibrium is stable when when the slope $\frac{d}{d\phi}(K_{NET})$ is positive. Figure 3-13 shows the variation of K_{NET} with roll angle at V = 30 knots for various sideslip angles (β) using the nominal XR-3 parameters. It is seen that for β less than 4°, a stable equilibrium is obtained at $\phi = 0$. For large β values a stable equilibrium is obtained at a value of ϕ which increases with β. At a value of β of about 8°, the equilibrium point reaches the limiting condition $\phi = \phi_{CR} = 10.4°$. For present purposes, this value of β, β_{CR}, is taken to define the limiting condition of stable operation.

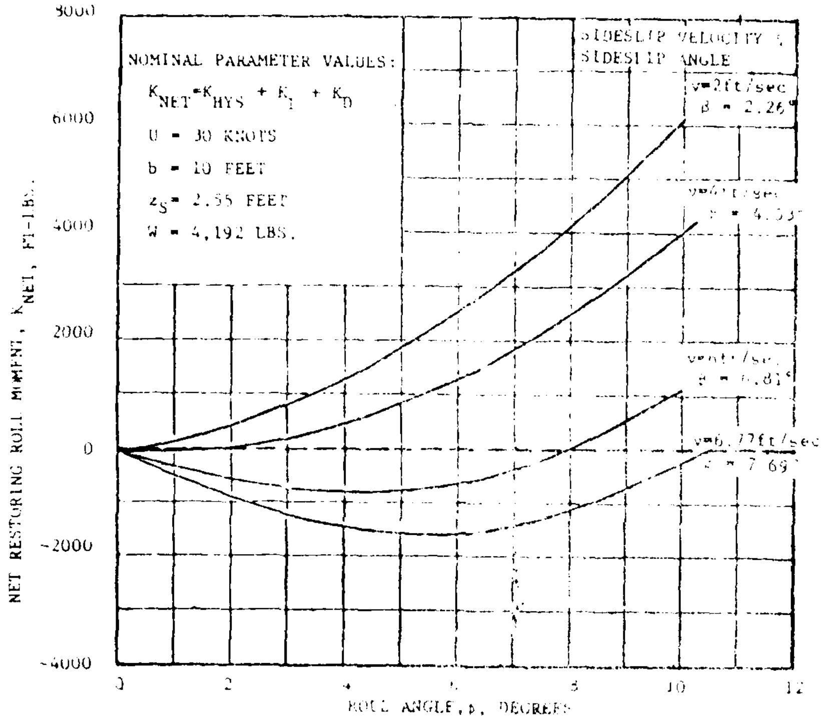


FIGURE 3-13. VARIATION OF NET MOMENT WITH ROLL ANGLE, U = 30 KNOTS, FOR VARIOUS β, NOMINAL XR-3 PARAMETERS. (AGC MAY 69)

Figure 3-14a shows that the limiting stability and condition, $K_{NET} = 0$ at $\phi = \phi_{CR}$, occurs for a value of sideslip angle β near 8° over the range of cushion density (p/ℓ) or weights shown, for the nominal length, beam, and other parameters. Also, over this weight range, a stable equilibrium is reached at $\phi = 0$ if the sideslip angle is less than 3.7 to 4.5 as shown in Figure 3-14b. Figure 3-14a also shows that the sideslip angle β_{CR}, for the limiting condition of equilibrium at ϕ_{CR}, is only slightly decreased by increasing the ratio of p/ℓ or by increasing weight.

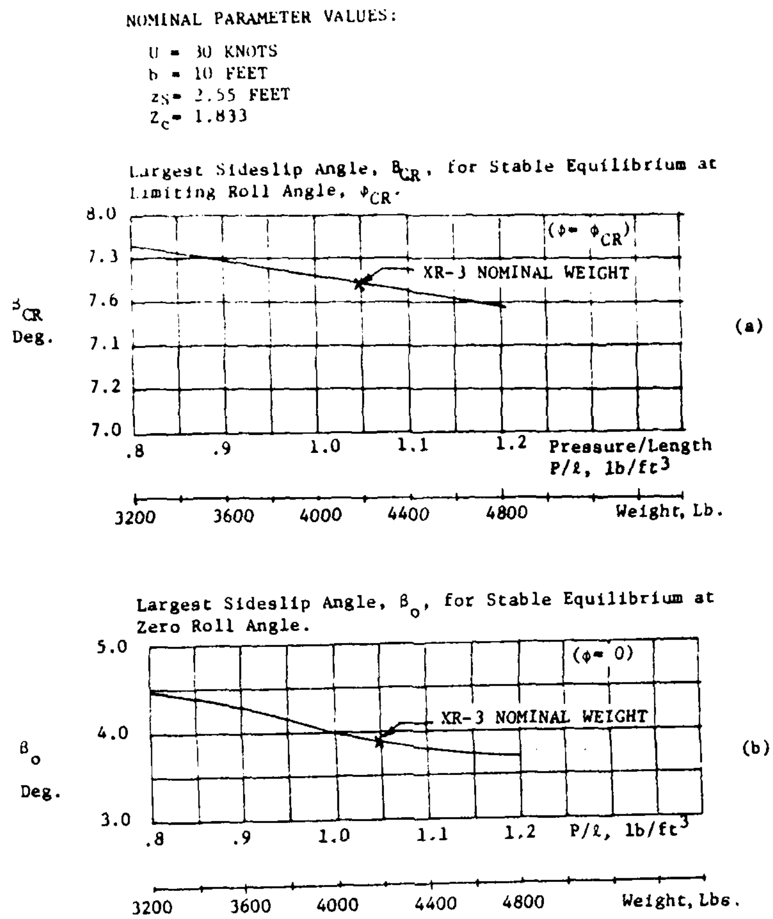


FIGURE 3-14. VARIATION OF SIDESLIP ANGLE WITH PRESSURE/LENGTH OR WEIGHT FOR LIMITS OF ROLL STABILITY. (AGC MAY 69)

The effect of length/beam ratio (ℓ/b) on the roll equilibrium is shown in Figure 3-15. For the smaller beam width (larger ℓ/b), no stable equilibrium can be reached at zero roll angle but, instead, the craft must be rolled to the angle shown in Figure 3-15b, (for example by $\phi = 10°$ for $\ell/b = 4.0$). However, for ℓ/b values less than 2.5, the vehicle can be stable at $\phi = 0$ even for small sideslip angles β. From Figure 3-15a, it is found that no side-slip angle can be tolerated (without rolling the vehicle more than the limiting condition $\phi = \phi_{CR}$), if the length to beam ratio ℓ/b exceeds 5.5.

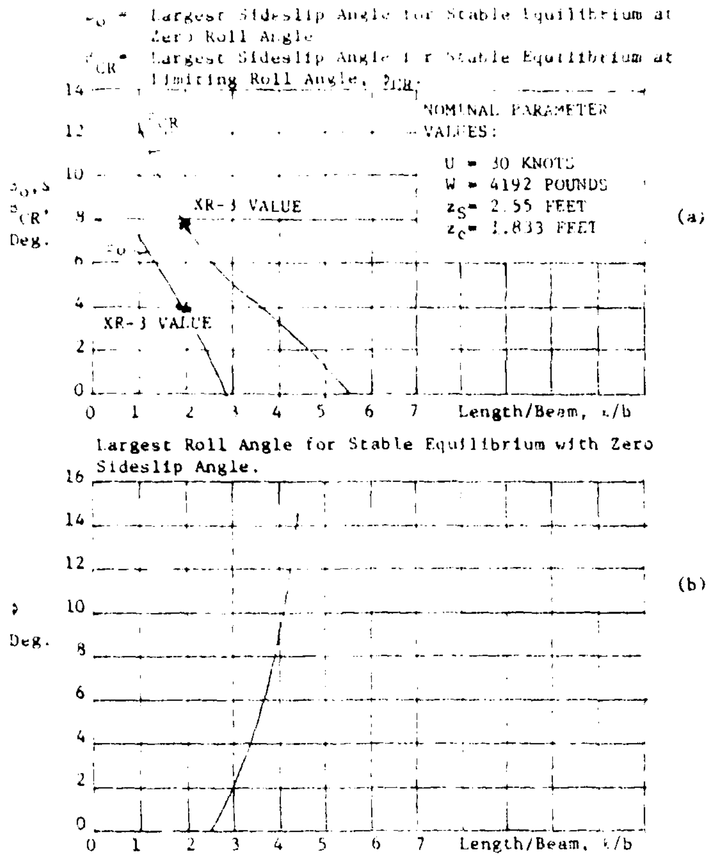


FIGURE 3-15. EFFECT OF LENGTH/BEAM RATIO ON ROLL EQUILIBRIUM. (AGC MAY 69)

The effect of vehicle c.g. height z_S on the roll stability is shown in Figure 3-16, for other parameters at the nominal XR-3 values. The roll stability is less for a high vertical c.g. position, but even at the large ratio of c.g. height to cushion height, $z_S/z_C = 1.64$, the craft is stable at zero roll angle (for sideslip angles of 3° or less), and the sideslip angle for stable equilibrium at the limiting condition $\phi = \phi_{CR}$ is 6.4°.

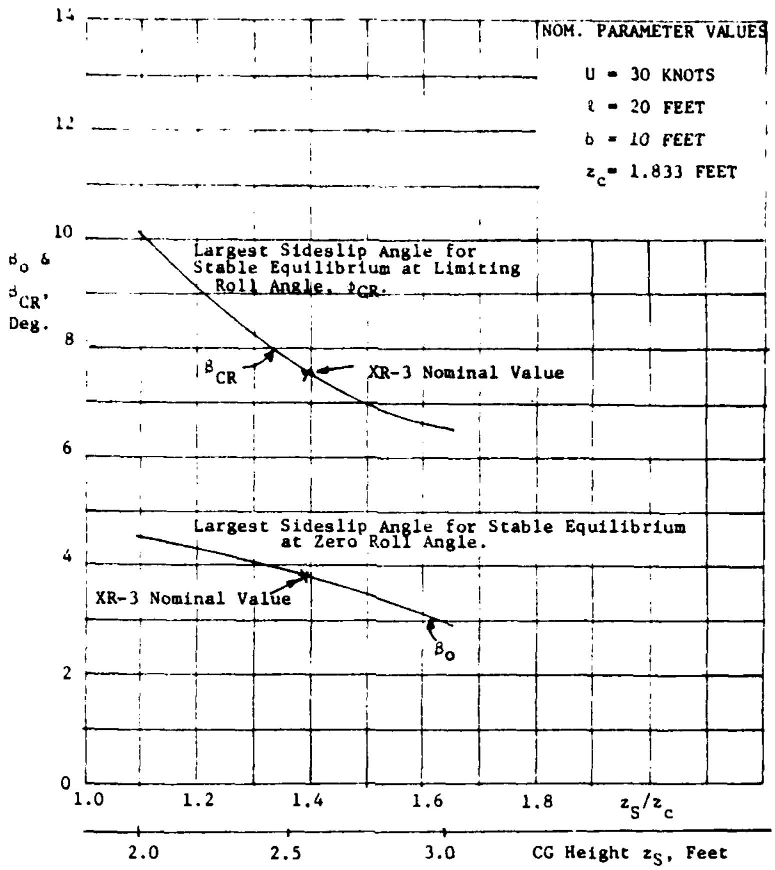


FIGURE 3-16. VARIATION OF SIDESLIP ANGLE WITH C.G. HEIGHT z_S FOR LIMITS OF ROLL STABILITY. (AGC MAY 69)

The effect of cushion height-to-beam ratio, z_C/b, on the limiting roll angle, ϕ_{CR}, was shown in Figure 3-9.At the higher ratios, the vehicle can roll further before wetting the wet deck. The effect of this ratio on the largest permissible sideslip angle for stable roll equilibrium is given in Figure 3-17. This figure shows that the ratio z_C/b only slightly affects the largest sideslip angle β_O for stable roll equilibrium at zero roll angle. The permissible side-slip angle β_{CR} for equilibrium at ϕ_{CR} increases considerably with z_C/b because of the increase in ϕ_{CR} versus z_C/b given earlier in Figure 3-9 (more roll can occur before the wet deck becomes immersed, when z_C/b is larger). For the larger immersion depths reached with increased z_C(d_S = 24 inches for z_C = 2 ft, d_S = 36 inches for z_C = 3 ft), the hydrostatic lift was assumed to increase linearly with immersion depth beyond the 22-inch limit used in earlier calculations of hydrostatic force.

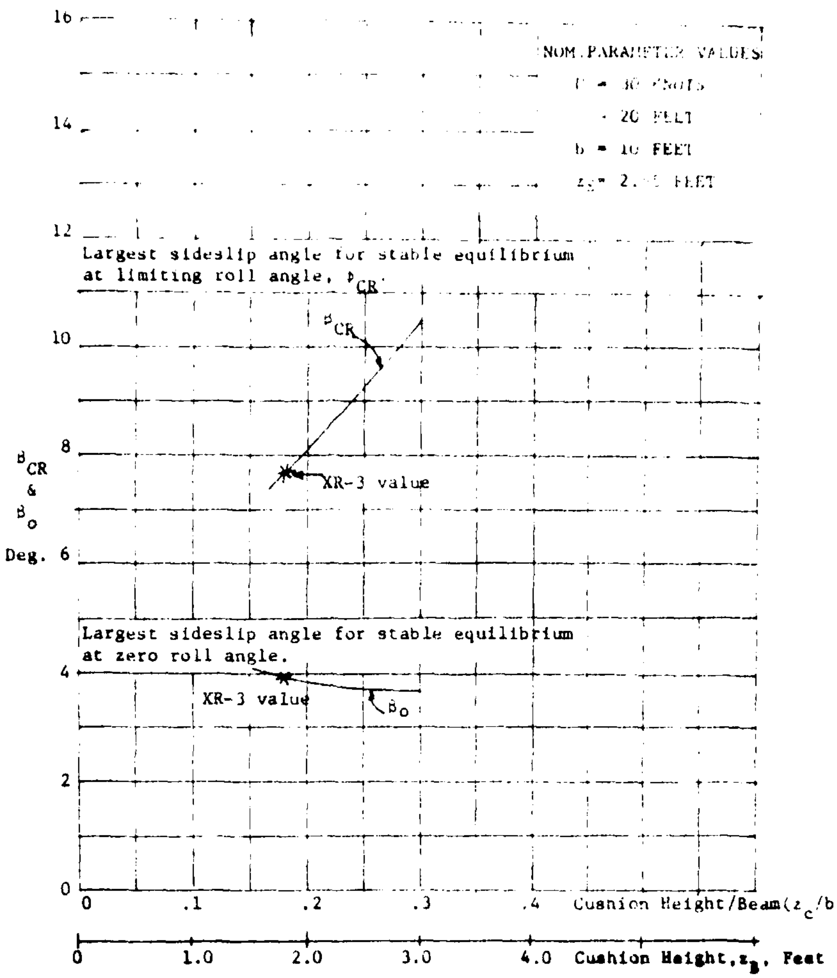


FIGURE 3-17. VARIATION OF SIDESLIP ANGLE WITH CUSHION HEIGHT/BEAM OR CUSHION HEIGHT FOR LIMITS OF ROLL STABILITY. (AGC MAY 69)

(b) Sway/Yaw Directional Stability on a Straight Line Course

The primary factor determining dynamic stability in the coupled-sway/yaw mode was shown by AGC to be the craft's pitch angle, and the sway/yaw mode was generally unstable for pitch-down of 2° or more. It was also observed that the sway/yaw mode becomes less stable as the sidehull immersion depth is increased up to depths of 15 inches, and then becomes more stable for further immersion. The effect of Froude number was minor, with the sway/yaw mode somewhat more stable at higher Froude number. The roll-mode stability decreased with Froude number, but the mode was still stable for Froude Number 4.

Shift in longitudinal c.g. location had minor effect on the dynamic stability, although the sway/yaw-mode stability was reduced for forward-c.g. location. Vertical shift in c.g. location had quite small effect on the dynamic stability, which depends much more on pitch angle and sidehull-immersion depth.

Interesting stability effects were found at deep-immersion depths corresponding to off-cushion operation, because the sway/yaw mode became more stable as the sidehull immersion depth (for the XR-3) increased beyond 15 inches and, for a depth of 20 inches, or more, the sway/yaw mode remained stable even for negative pitch angles as large as -4°.

The conclusions about vehicle stability for shift in longitudinal-c.g. location agree in a general manner with the XR-3-testcraft experience, where the craft had satisfactory stability, with the main effect of longitudinal-c.g. shift coming from change in pitch angle. The trim pitch angle has a strong effect on the vehicle's drag; and also negative pitch attitudes lead more easily to plow-in or, as shown in the AGC analytical studies, to reduced dynamic stability for a straight-line course.

The sidehull-immersion depth/pitch angle envelopes that define the limits of the region of these parameters, where the craft first becomes statically unstable in yaw and then becomes dynamically unstable in the sway/yaw mode, are presented in Figure 3-18. These envelopes were based upon consideration of the uncoupled sway/yaw motion. It was anticipated by AGC that the negative pitch angle would not destabilize the roll mode and the coupling with the roll mode would not very significantly alter the effect of the negative pitch angle on the stability of the sway/yaw mode. Calculation of the coupled stability roots for negative pitch-angle conditions, confirmed these expectations.

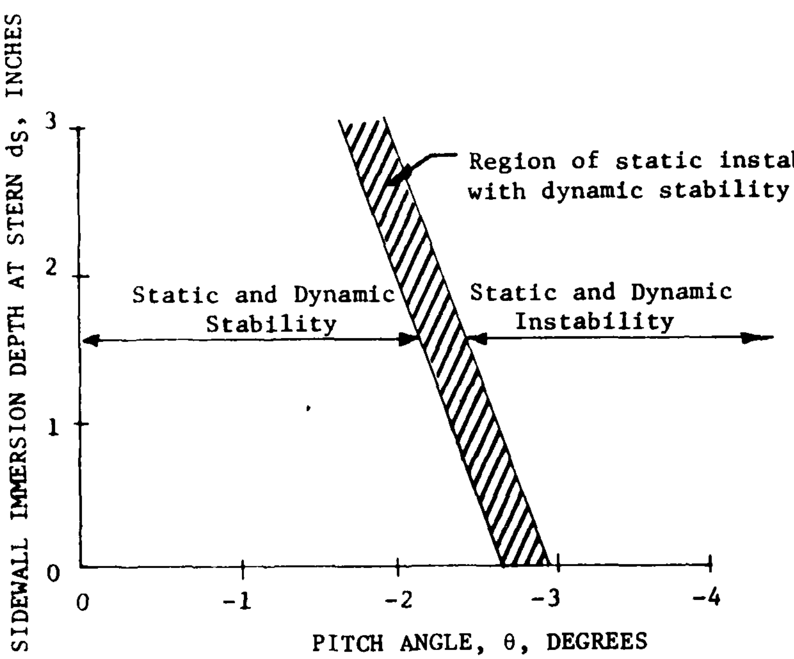


FIGURE 3-18. YAW/SWAY MODE STATIC AND DYNAMIC STABILITY ENVELOPES FROUDE NUMBER 2.0. (AGC MAY 69)

Figure 3-19 shows the stability envelopes obtained from computations of the coupled roots. The envelope (dashed) line was obtained by interpolations between the computed points (circles) as shown. These envelopes indicate a small dependence on Froude number and a somewhat larger stable region than obtained with the uncoupled roots, ie the coupling tends to improve the stability of the sway/yaw mode. Because the roll mode was always stable, the envelope is determined by the sway/yaw mode stability.

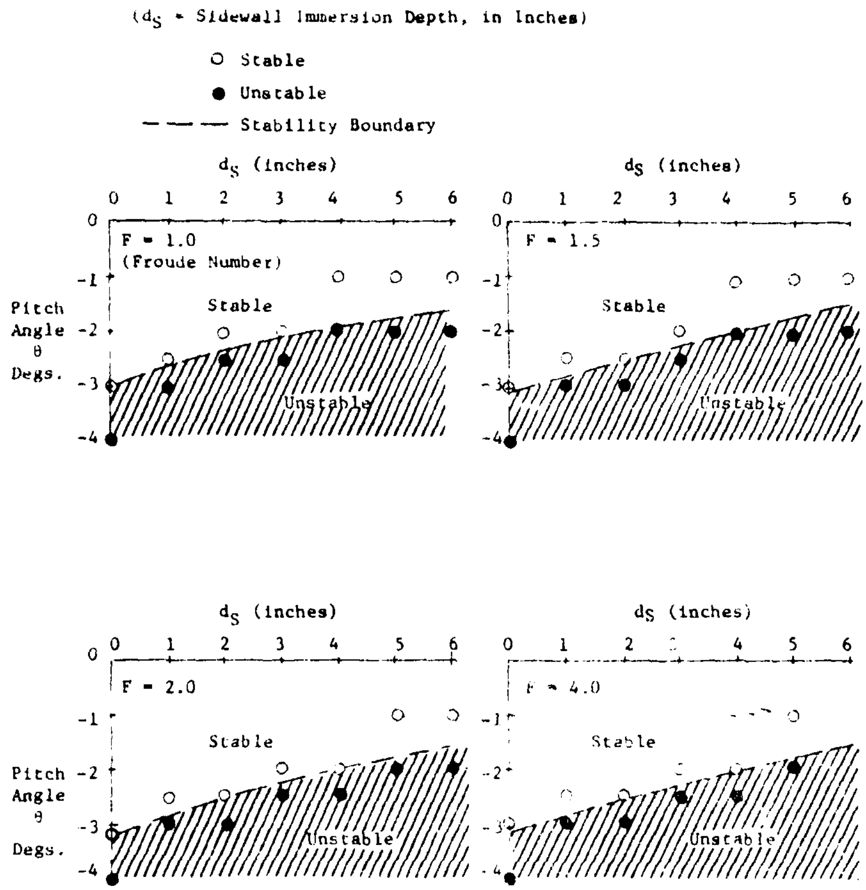


FIGURE 3-19. DYNAMIC STABILITY ENVELOPE, FOR COUPLED YAW/SWAY MOTION ALONG A STRAIGHT LINE COURSE, USING NOMINAL PARAMETER VALUES FOR THE XR-3. (AGC MAY 69)

AGC also explored yaw/sway stability for various conditions in the transition from off to on-cushion and results were calculated for sidehull immersion depths beyond the value d_S = 6 inches discussed above. For on-cushion operation, a sea state approaching 2 would be required to produce an equivalent time average immersion depth beyond 6 inches. However, for off-cushion operation, the sidehulls would be immersed their full depth of d_S =22 inches.

The resulting operational envelopes, found for various sidehull immersion depths and pitch angles, are shown for the low-speed condition, Froude Number 0.3, in Figure 3-20. This shows that a considerable region exists in which the craft is actually dynamically stable, although the static stability, is unfavorable. Thus, the craft can hold a straight-line course in the larger region of dynamic stability. At deep immersions the vehicle is dynamically stable even for negative pitch angles to -4°. (A region of dynamic instability where the craft is controllable by the rudder is also shown on Figure 3-20) Similar results were found for Froude Numbers 0.5 and 1.0, though the shaded region of static instability with dynamic stability was smaller at the higher speeds.

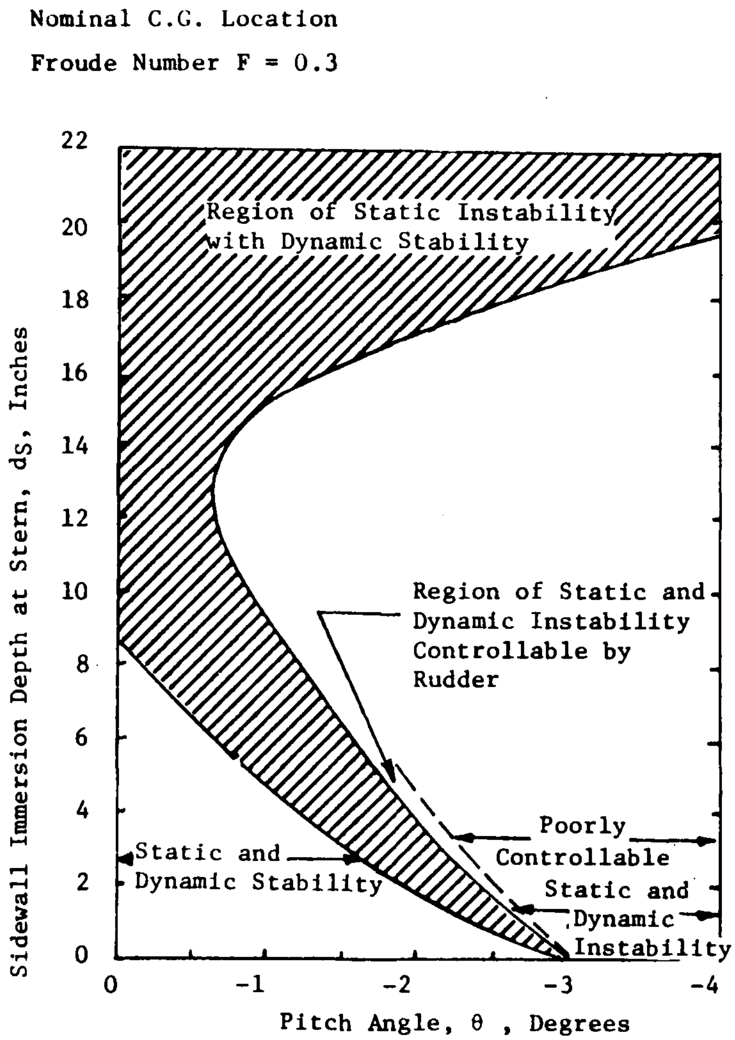


FIGURE 3-20. CONTROLLABILITY AND STABILITY BOUNDARIES, F = 0.3. (AGC MAY 69)

The operating envelopes of stability are shown for Froude Number 2 in Figure 3-21, for immersion depths up to 6 inches, and again shows that the craft is dynamically stable for a range of negative pitch angle larger than the limits of static stability. Results for Froude Number 4 were very similar to Figure 3-21.

Nominal C.G. Location

Froude Number F = 2.0

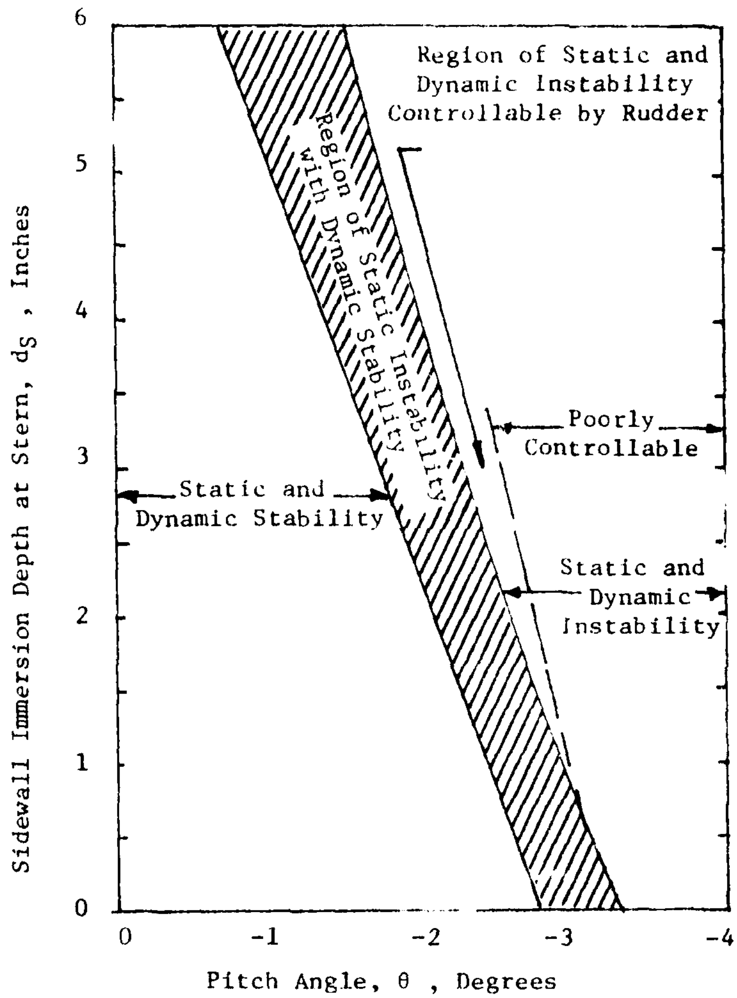


FIGURE 3-21. CONTROLLABILITY AND STABILITY BOUNDARIES, F = 2.0.(AGC MAY 69)

The operating envelopes shown in Figures 3-20 and 3-21 may be used to determine the region of static stability at various sea states by determinations of the effective sidehull immersion depth d_S for the sea state, through use of Table 3-2. For a vehicle of different size than the XR-3, comparison should be made for the same nondimensional values of $\frac{d_S}{\ell}$ where ℓ is the reference cushion length (ℓ = 20 ft for XR-3).

TABLE 3-2. RELATIONSHIP BETWEEN SEA STATE AND IMMERSION DEPTH.

SEA STATE	XR-3 IMMERSION DEPTH d_S, inches	DIMENSIONLESS IMMERSION d_S/ℓ
1	.221	$.910 \times 10^{-3}$
2	.663	2.76×10^{-3}
3	1.11	4.60×10^{-3}
4	1.77	7.35×10^{-3}
5	2.65	11.11×10^{-3}
6	4.42	18.4×10^{-3}
7	8.84	86.9×10^{-3}

3.3.3 Rohr 1978

The general stability criteria defined to guide the early development of the 3KSES were as follows:

(a) Normal variations in static disturbance moments shall not result in attitude variations of a magnitude sufficient to affect controllability or significantly degrade craft performance.

(b) Subsystem component failures shall not result in uncontrollable divergent motions or dangerously large attitude excursions.

(c) Changes in operating conditions shall not require excessive cg shifts to arrive at acceptable (not necessarily optimum) running trim.

(d) Dynamic responses in waves shall be maintained to satisfy applicable habitability criteria and to avoid dangerously large attitude excursions.

Subsequent development of the 3KSES design (ROHR 31 AUG 78) resulted, in a more demanding requirement expressed as an expansion of item (b) above.

The stability criteria discussed in ROHR 31 AUG 78 require that the ship be controllable for any single independent failure. The response of the ship to any failure is taken to exhibit satisfactory controllability if its attitude does not go beyond 75 percent of the lesser of (a) the envelope of static stability or (b) the range of available static stability data. Because the ship is stable for all attitudes measured during model tests, 75 percent of (b) is the governing boundary, illustrated by Figure 3-22 for roll and drift angles at various speeds. The boundaries in Figure 3-22

are applicable to the range of trims indicated. This covers the normal operating trim with adequate allowance for down-trim to the conditions for minimum directional stability. It should be emphasized that even the limits of stability data (one-third greater than on Figure 3-22) do not in any way imply that instability lies just outside. Knowledge of such conditions is not available. It is sufficient to show that the motion of the ship under critical conditions will remain well within known safe attitudes.

For symmetric failures (vertical plane), the criteria for safe response are met without operator intervention. Some asymmetric failures, however, require corrective action. In these instances, it is shown that the ship is readily controllable solely by a human pilot. Automatic stabilization devices, while superior in the control of failure response, are shown to be unnecessary for safe control of the ship.

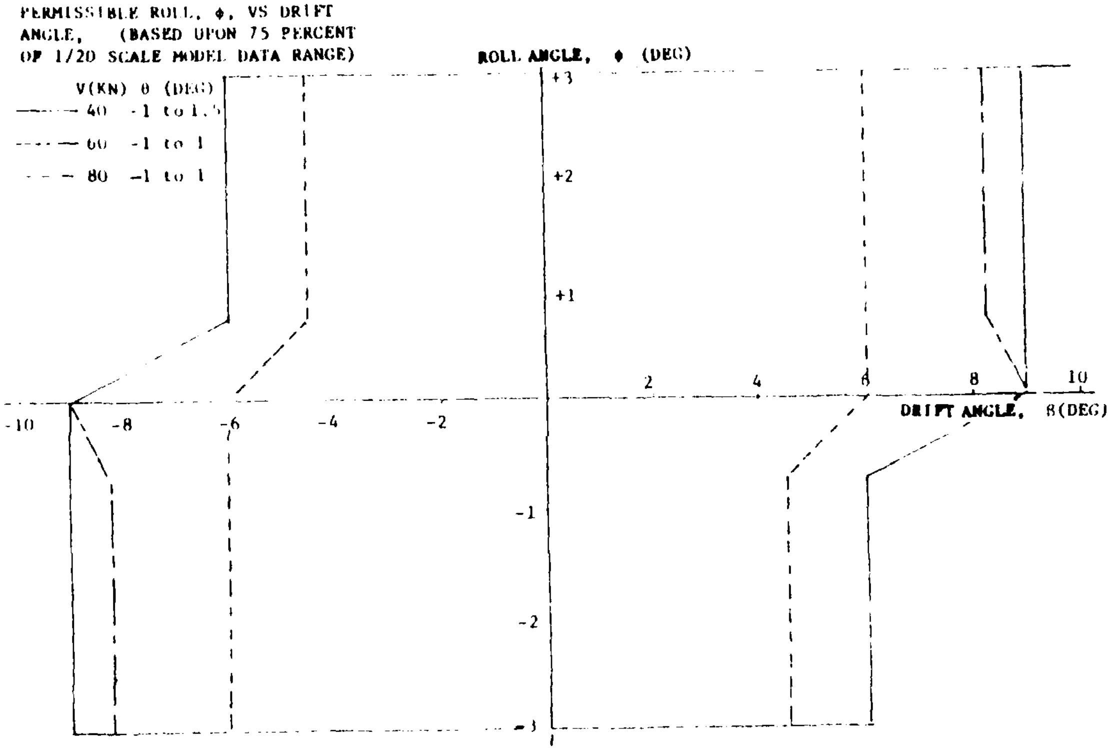


FIGURE 3-22. OPERATING BOUNDARIES OF ROLL-DRIFT ANGLES.

3.4 STABILITY STANDARDS FOR AMPHIBIOUS ACVs WHILE OPERATING IN THE ON-CUSHION MODE

No widely accepted stability standards exist for amphibious ACVs. As was the case with the SES, adequate stability, over the years, has been judged principally from the experience of model and full-scale testing. As a result of this background, some basic design guidelines have evolved and these are discussed below: -

3.4.1 Pitch and Roll Static Stiffness

The level of pitch and roll static stiffness as measured during overland hovering tests (or underway overwater tests) has appeared as the only measure of stability which has received some universal recognition. This is apparently because its measurement is relatively easy to achieve. Although in itself it conveys little regarding the craft's ultimate ability to resist a capsize, the possible lack of stiffness can be used as an indication of potential problems if values are outside of present day experience.

The pitch and roll stiffness of an ACV is typically expressed as the percentage shift in center of cushion pressure which results from a 1 degree change in roll (or pitch) angle qualified by the linear range over which it is applicable and is written as:

$$\hat{K} = \%\ \text{c.p. shift/degree} = \left(\frac{M}{WL} \cdot 100\right)$$

where M = moment to incline the craft through 1 degree

W = craft weight

L = cushion reference length (length or beam)

This, of course, is similar to the metacentric height (GM) used for assessing the initial stiffness of displacement ships. The transverse metacentric height, for example, can be expressed as:

$$GM_T = \frac{K}{W \sin\phi} = \hat{K}\left(\frac{57.3}{100}\right) B$$

where K = the righting moment for a small angle of roll ϕ

W = ship displacement

$\hat{K}$ = % c.p. shift/degree

Pitch and roll stiffness for an ACV can be fairly non-linear. The range of applicability of quoted stiffness values is usually of the order of $\pm 3°$. Some ACVs, which have operated satisfactorily, are unstable in pitch and/or roll for small angles (e.g. $\pm 0.5°$), in which case, the stiffness is averaged over the range of say $\pm 0.5°$ to $\pm 3°$.

It has become recognized that small, highly maneuverable ACVs, can be satisfactorily designed with overland roll stiffness values of 0.5% B/deg or higher and with overland pitch stiffness values of twice this value. ACV stiffness, while underway overwater will, in general, be a little lower than values measured overland, although at high speed, pitch stiffness, in the bow-down condition, can diminish to very small values as discussed later under the subject of plow-in. For large commercial ACVs, British Hovercraft Corporation (BHC) have recommended (CAA JUN 75) roll-stiffness values in the range of 1% to 2% c.p. shift per degree (with pitch values of about twice these values).

The choice of stiffness should also recognize the range of C.G. shift required of the craft. BHC craft have been considered satisfactory if lateral C.G. shifts of 3% to 9% can be sustained prior to significant skirt tuck-under. (CAA JUN 75) (See later discussion of skirt tuck-under and plow-in.) The actual shift value depends upon the particular design and should provide a safe margin over the worst possible combinations of upsetting moments including (a) control-force moments (b) wind moments (c) wave action (d) maximum likely actual C.G. offset (CAA JUN 75). During design, one of the most important parameters is the C.G.-height-to-cushion-beam ratio. Because C.G. height has a destabilizing effect proportional to roll angle it detracts from the cushion forces which provide for roll and pitch stiffness. Also, the larger the C.G. height in relation to beam the larger will be the destabilizing moments in relation to stabilizing moments during turning maneuvers. Thus, in general, the larger the C.G. height the larger the pitch and roll stiffness should be.

Figure 3-23 shows for several existing ACVs (and SES) roll stiffness values for corresponding values of cushion height to cushion beam ratio. Cushion height (taken as the wet deck clearance height) is generally, (when comparing various designs), in approximate fixed proportion to C.G. height. Figure 3-24 shows, for a number of craft, for which nominal C.G. heights were known, that the C.G. height is, on average, about twice the height of the wet deck or cushion height.

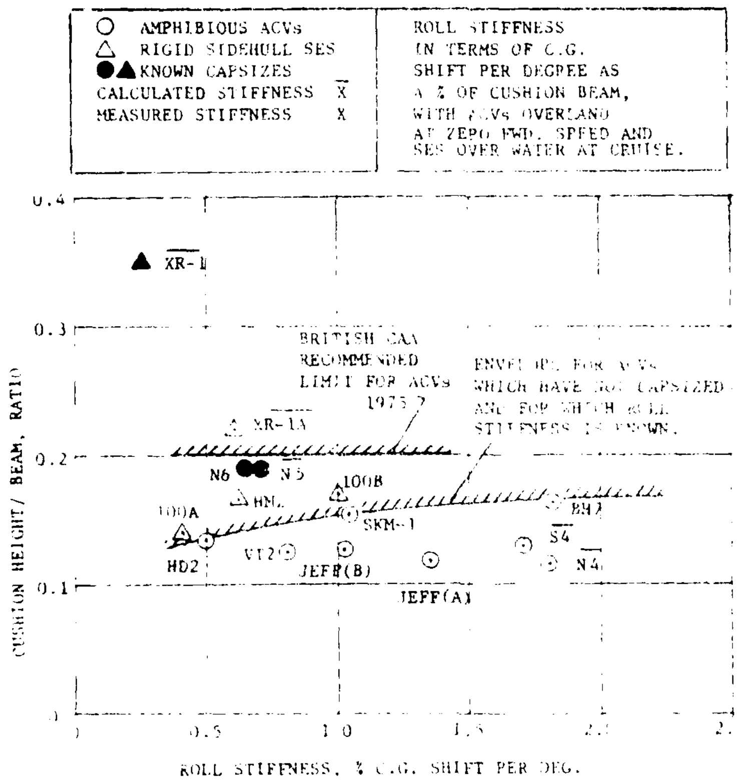


FIGURE 3-23. ROLL STIFFNESS, IN RELATION TO CUSHION HEIGHT TO BEAM RATIO FOR VARIOUS EXISTING ACVs.

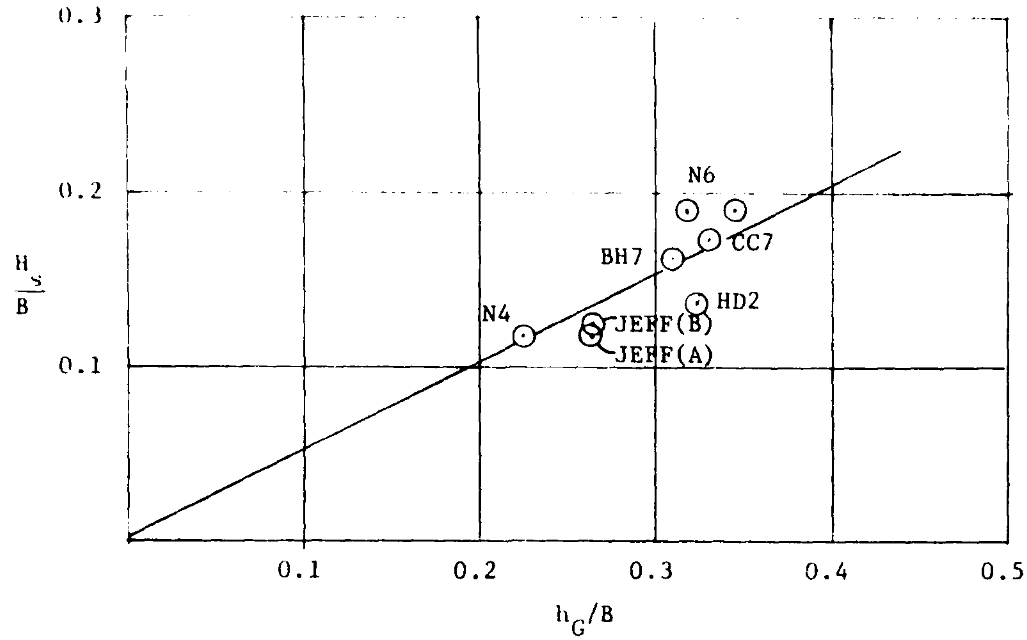


FIGURE 3-24. CUSHION HEIGHT IN RELATION TO C.G. HEIGHT FOR A RANGE OF EXISTING ACVs.

With cushion height instead of C.G. height as the principal parameter, Figure 3-23 shows ACV overland roll-stiffness values ranging from 0.5 to 1.8% C.G. shift per degree with cushion-height-to-beam ratios less than the British CAA recommended limit of 0.2 (CAA JUN 75). Excluding the SR.N5 and SR.N6 craft (which have in fact capsized) Figure 3-23 shows a slight trend towards higher roll stiffness with craft of higher cushion-height-to-beam ratios. This is indicated by the envelope (curve) for ACVs which have (so far) not capsized in operation. The selection of roll stiffness values equal to or greater than those indicated by the envelope of current day experience on Figure 3-23 could be considered safe practice, with adequate margin, since all vehicles below the line have behaved satisfactorily.

3.4.2 Pitch and Roll Dynamic Stability

(a) Plow-in

The principal concern for ACV dynamic stability underway has been the provision for adequate resistance to skirt tuck-under and plow-in. Plow-in can occur in smooth or rough water and is accentuated by operation with off-set C.G. locations, high speed and reduced cushion air flow rate. Plow-in is due to the development of either nose-down and/or rolling moments causing greater than normal skirt contact with the water. This additional contact will increase the drag forces acting on the skirt and will cause the skirt hemline to "tuck-under" which will tend to distort the bow skirt (support) bag rearwards, thus moving the center of area of the cushion aft to cause a loss in available aerostatic restoring moment. This loss in restoring moment is accentuated by the increased bow down moment due to skirt drag causing

further bow-down and/or rolling attitude and hence further skirt immersion and drag. The plow-in is characterized by a rapid deceleration combined with large bow-down (4° or greater) and/or roll attitude with a tendency for directional instability and the development of large (generally) uncontrolled angles of yaw. The danger is that at some time during this maneuver, relatively high speed beam-on (pure sideways) motion can occur.

Since the available restoring moments in roll are less than in pitch the destabilizing moments described above can create extreme angles of roll, causing hard structure contact and the possibility of an eventual capsize in roll as discussed later.

To prevent skirt tuck-under and plow-in, the bow and side skirts are designed to resist, as much as possible, the tendancy to deform horizontally under load. This is controlled in design by the choice of skirt inflation pressures and geometry.* For a given design, operational limits are usually placed on the allowable off-set C.G. location, forward speed and cushion-air-flow rate combinations.

Figure 3-25 (BLA JUL 79) shows the apparent tuck-under inception boundary for the U.S. Navy's AALC JEFF(B) bow skirt as a function of forward speed and C.G. location as derived from full-scale trials. These full-scale results are compared in Figure 3-26 with results of testing a 1/12th-scale model of the JEFF(B) having the same skirt geometry. Although the full-scale data was obtained very early in the JEFF(B) test program, and at a time when skirt improvements were being made, it was apparent, from the comparison of Figure 3-26, that the model-test technique, or scale effects, resulted in the prediction of a far more optimistic C.G. shift capability than was initially achieved at full scale. The purpose for presenting Figure 3-26 is, therefore, to illustrate the potential danger of relying on predictions based exclusively on model-scale data.

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* including the installation of anti-tuck-under bags etc.

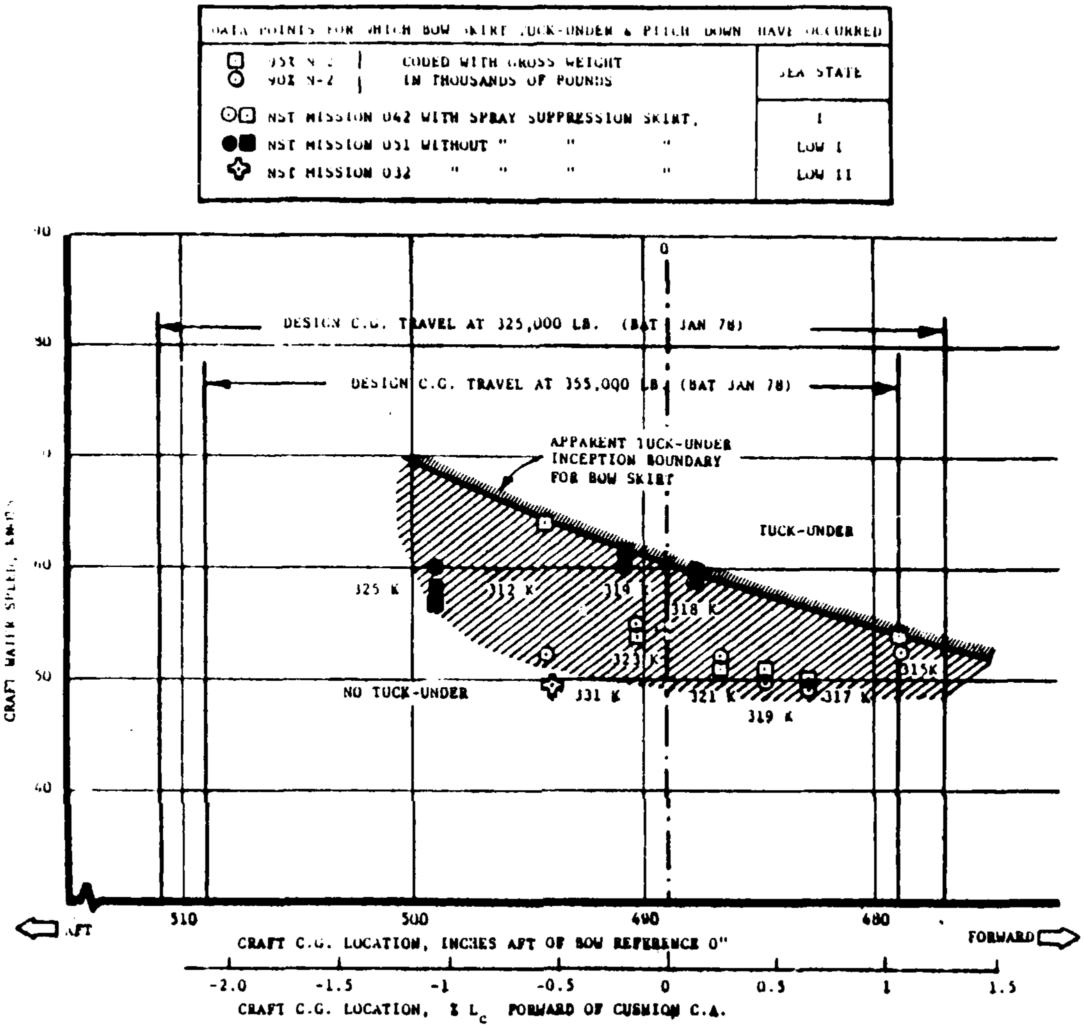


FIGURE 3-25. JEFF(B) BOW SKIRT TUCK-UNDER INCEPTION BOUNDARY FROM NST MISSIONS 032, 042 and 051.

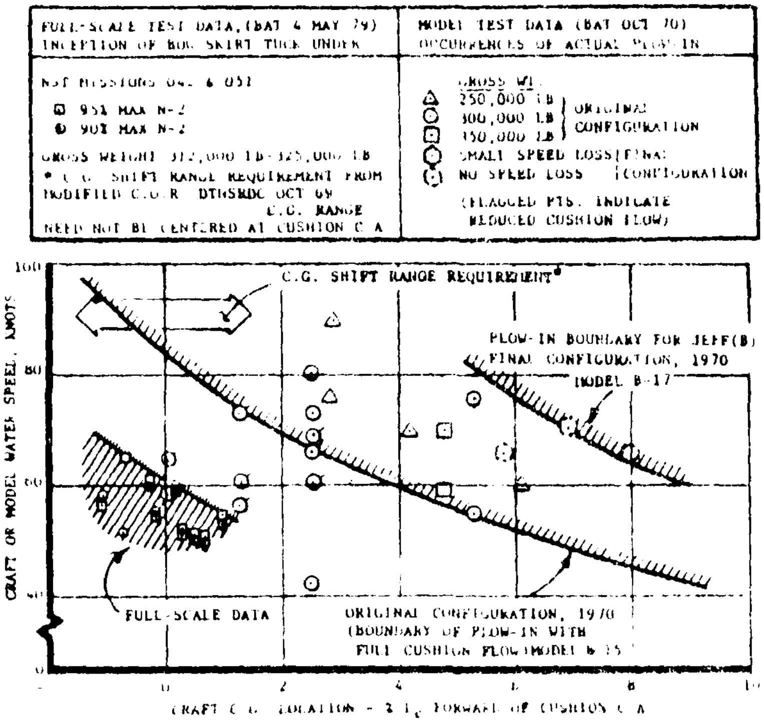


FIGURE 3-26. JEFF(B) PLOW-IN BOUNDARY SCALED FROM 1/12th SCALE MODEL TESTS IN COMPARISON WITH FULL SCALE SKIRT TUCK-UNDER INCEPTION BOUNDARY.

(b) Operation at Large Side-Slip Angles

Once the plow-in boundary of a craft has been established, from either full-scale test results or from adjusted model-scale test results, operation within the boundary will allow the avoidance of skirt tuck-under and craft plow-in during normal zero-sideslip operation.

During turning maneuvers, however, relatively large side-slip angles can occur. If the maneuver is made at high speed and the sideslip angle and velocity are high, then a danger of side-skirt tuck-under can exist. Thus, regulatory authorities have, in the past, imposed operational speed - sideslip angle boundaries for commercial craft as illustrated for the SR.N5 in Figure 3-27 (from CAA JAN 77). This type of restriction was first introduced by BHC and is still in use for all British commercial ACVs.

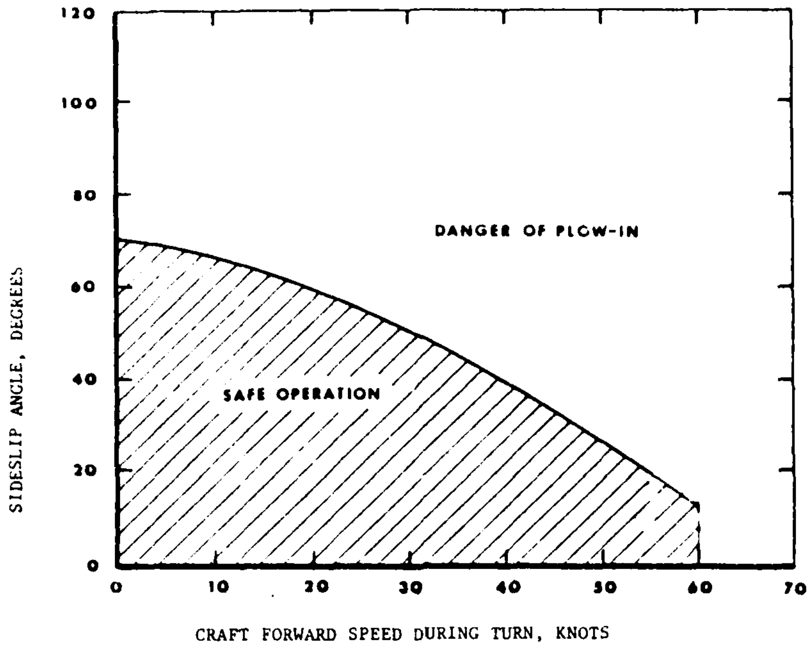


FIGURE 3-27. SR.N5 SPEED-SIDESLIP BOUNDARY. (CAA JAN 77)

(c) Capsize in Roll

In all ACV capsizes, to date, the craft were found to have been traveling sensibly beam leading (i.e. sideways) at sometime during the capsize. Since the first commercial ACV capsize in April 1965 considerable attention has been given to the mechanism of roll capsize. In the U.S., the early SR.N5 and Hydroskimmer work of Bell Aerospace under contract to BUSHIPS was particularly significant. (See Background Study Volume I "Master Report".) Of greater significance, however, has been the more recent work published by the British Civil Aviation Authority in June 1975. This report summarizes the information on hovercraft capsizing available to the U.K. Air Registration Board Special Committee on Hovercraft Stability and Control. A list of all known overwater commercial-sized craft capsizes along with all known overland capsizes of recreational-sized hovercraft is given. Where known, a brief discussion of the capsizing and the events leading to the capsizing for particular craft are included. Also included, where known, is a list of craft particulars (geometric parameters) of the craft involved. From this investigation of capsizing events and craft particulars some of the factors affecting capsizing, with particular reference to geometric parameters, are brought out and recommendations are made on a range of suitable values of design parameters considered most critical to minimize the risk of capsizing. These are reproduced in Tables 3-3 and 3-4. Table 3-3 lists the design factors affecting the leading sideskirt tuck-under boundary. The range of current practice is quoted but it was stated that these values should not be regarded as design rules or limiting values. The same comment applies to Table 3-4 which lists other design factors affecting the craft's reserve against capsizing, again up to the point of skirt tuck-under.

Various conclusions and recommendations are made in the report regarding craft design, model and full scale testing and operational aspects to minimize the risk of capsizing.

TABLE 3-3. DESIGN FACTORS AFFECTING LEADING SIDESKIRT TUCK-UNDER BOUNDARY. (CAA JUN 75)

Sectional Geometry Parameters	Comment	Current Practice
$\frac{z_H}{x_H} = \frac{\text{Hinge vert. spacing}}{\text{Hinge horiz. spacing}}$ *	High value favourable	0·15 to 1·0
$\frac{p}{x_H} = \frac{\text{Bag perimeter}}{\text{Hinge horiz. spacing}}$	High value favourable at lower pressure ratios (p_B/p_c)	1·75 to 3·5
$\frac{b}{x_H} = \frac{\text{Cushion beam}}{\text{Hinge horiz. spacing}}$	Low value favourable	5·0 to 7·5
Percentage finger depth	Low value favourable, in theory, but some minimum value (> 20%) probably optimum in practice, due to better drag characteristics of finger than bag, even on purely beam-on considerations	
Overall Skirt Geometry and Craft Parameters		
Compartmentation	Centre keel, with differential pressure in roll favourable, unless p_B/p_c for leading sideskirt becomes low and z_H/x_H and/or p/x_H are low.	
$\frac{H_{SK}}{b} = \frac{\text{Skirt Depth}}{\text{Cushion Beam}}$	Low value favourable	0·10 to 0·20
$\frac{p_B}{p_c} = \frac{\text{Bag pressure}}{\text{Cushion pressure}}$	High value favourable	1·0 to 2·0
C_Δ = Cushion loading	High value favourable	0·01 to 0·03
$\frac{b.t.c}{H_{SK}} = \frac{\text{Buoyancy tank clearance}}{\text{Skirt depth}}$	High value favourable	0·8 to 1·1
$\frac{b}{l_e} = \frac{\text{Cushion beam}}{\text{Effective cushion length}}$	Low value favourable, in conjunction with H_{SK}/b and C_Δ but only $\sqrt{b/l_e}$ is as powerful as these.	0·4 to 0·75
Wetting drag coefficient	Low value favourable, but unlikely to be very different from model value, i.e. of order 0·01.	

NOTE: The above statements and numerical ranges, which reflect design practice for several current craft, are provided for general guidance and not as design rules or limiting values. An overall configuration involves a compromise choice of all the factors, and may be satisfactory even if one or more factors are at the least favourable end of the range.

* Z_H = Vertical spacing between inner and outer attachment points of the skirt loop to the hull structure.

X_H = Horizontal spacing between inner and outer attachment points of the skirt loop to the hull structure.

TABLE 3-4. DESIGN FACTORS AFFECTING CRAFT'S RESERVE AGAINST CAPSIZING (UP TO TUCK-UNDER POINT).(CAA JUN 75)

Parameter	Comment	Current Practice
$\frac{57.3}{8} \frac{\partial(\Delta p/p_c)}{\partial\phi} - \frac{h_G}{b}$ * * Differential pressure rate less CG height moment parameter	A high value is favourable in this context, but will be offset by an adverse adjustment to the tuck-under merit if hinge spacing and bag perimeter ratios are not good (unless initial pressure ratio is high).	–0·3 to 0·6
$\frac{b.t.c}{H_{SK}} = \frac{\text{Buoyancy tank clearance}}{\text{Skirt depth}}$	The importance of this parameter is modified by the size of the 'drag moment' parameter, but a high value is favourable	0·8 to 1·1
$\frac{h_G/b}{C_\Delta} = \frac{\text{CG height ratio}}{\text{Cushion loading parameter}}$	Drag moment parameter. Low value favourable.	10 to 25
$\frac{p}{x_H} = \frac{\text{Bag perimeter}}{\text{Horiz. hinge spacing}}$	Affects beam increase. High value favourable.	1·75 to 3·5
$\frac{p_B}{p_c} = \frac{\text{Bag pressure}}{\text{Cushion pressure}}$	Affects bag pressure moment. High value favourable.	1·0 to 2·0
$\frac{b}{x_H} = \frac{\text{Cushion beam}}{\text{Horiz. hinge spacing}}$	Relates skirt contact moment to cushion beam dependent and other moments. Low value favourable.	5·0 to 7·5

NOTE: **The above statements and numerical ranges, which reflect design practice for several current craft are provided for general guidance and not as design rules or limiting values. An overall configuration involves a compromise choice of all the factors, and may be satisfactory even if one or more factors are at the least favourable end of the range.**

* Δp = difference in cushion pressure between port and starboard side of longitudinal stability trunk.

$\partial\phi$ = change in roll angle, degrees.

b = cushion hemline beam, ft.

h_G = height of C.G. above mean water plane, ft.

$C_\Delta = W/(\rho_h g (S_c)^{3/2})$; S_c = cushion area, ft^2

ρ_h = mass density of water, $slugs/ft^3$

W = craft gross weight, lb.

The Committee recognized that many problem areas had been highlighted and therefore further general research was recommended, not only to increase basic data and knowledge, but also to enable better theoretical techniques to be formulated. Accordingly, a general research program based on the Committee's recommendations was formulated by the CAA, BHC and others in the hovercraft industry, and results of the program being conducted for the British Department of Trade and Industry are expected to be published in early 1980.

One of the particularly hazardous situations of concern for ACVs is the beam-on wave over-turn situation as encountered with the SR.N6-012 in March 72 when five out of a total of 26 passengers lost their lives in severe weather conditions off Spithead, in the Solent, England. Figure 3-28 shows the general situation and Figure 3-29 illustrates the reported capsizing event. According to WRAITH of the (CAA JAN 77), SR.N6-012 left Ryde for Southsea and capsized approximately 400 yards from the Southsea base. At the point of capsize the mean wind was approximately 30 knots, gusting to nearly 45 knots. The wind was blowing on the craft starboard beam and in almost direct opposition to the 2-1/2 to 3 knots tidal stream coming out of Portsmouth Harbour. There was consequently a short steep sea with waves, estimated at the time, to be six to eight feet high and up to sixty feet long. Figure 3-29 from CAA JAN 77 summarizes the information on the accident provided by eye witnesses who included an N6 Commander who was watching the craft approach.

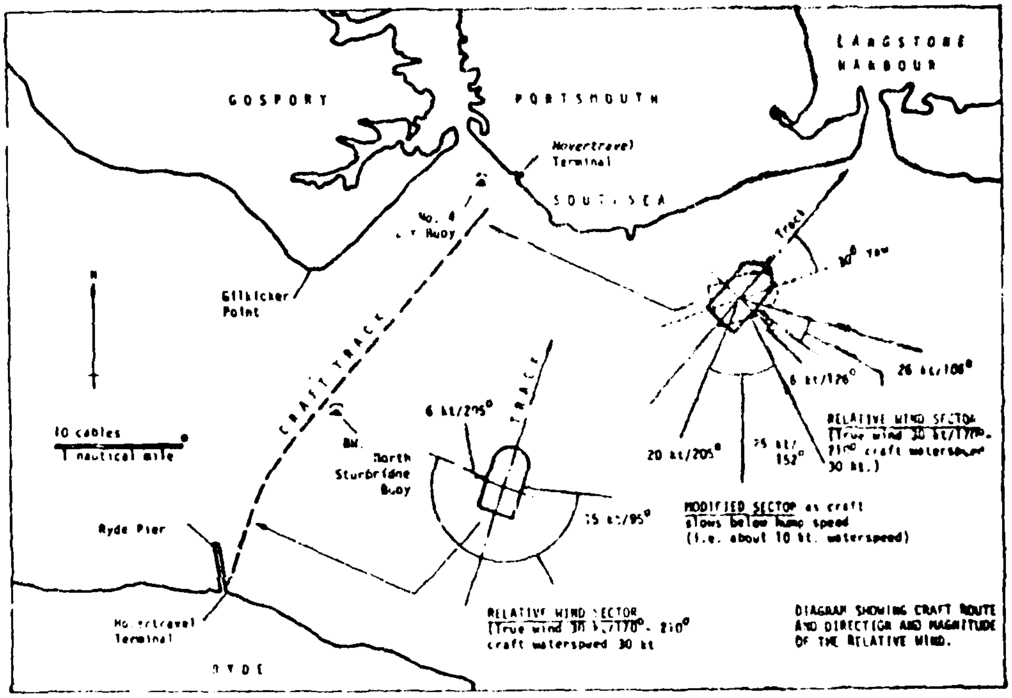


FIGURE 3-28. CHART OF SPITHEAD ILLUSTRATING THE SR.N6-012 CAPSIZE, MARCH 1972,(CAA JAN 77).

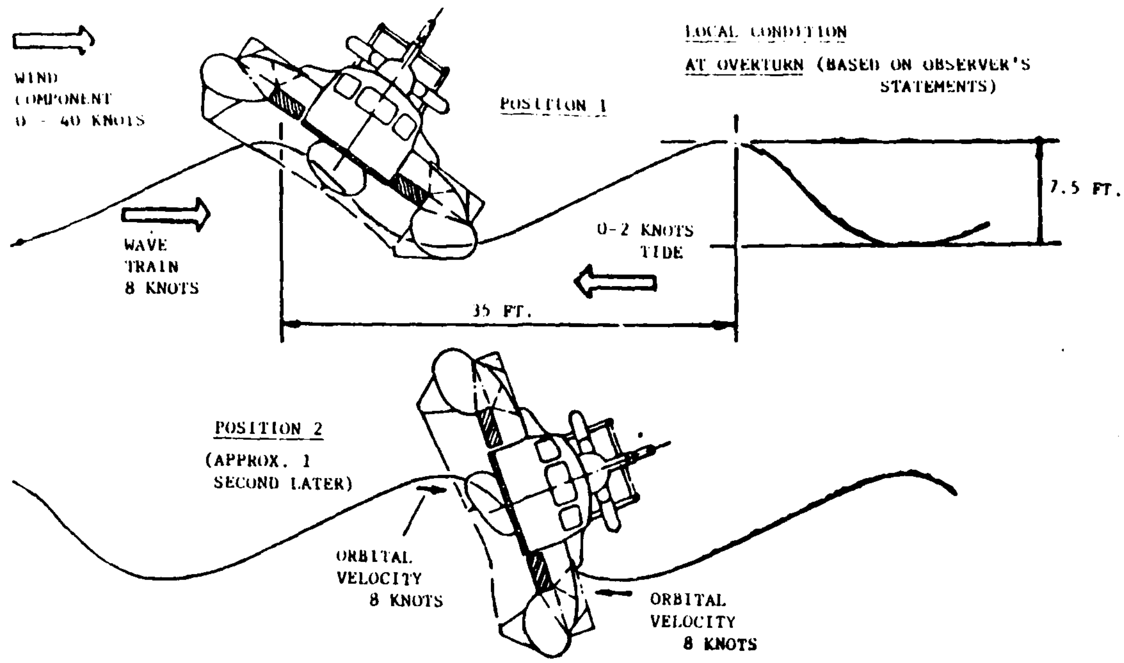


FIGURE 3-29. ILLUSTRATION OF SR.N6-012 CAPSIZING EVENT (CAA JAN 77).

After the accident, BHC worked day and night to try to establish the cause, by means of model tests and theoretical analyses. Almost immediately they published a Service Bulletin which drew attention to the danger of decelerating with sideways motion, particularly when using low-turbine rpm.* This was followed a few days later by another bulletin, which described in full-scale terms the results of the model tests. It was found, that the craft could, occasionally, be made to overturn in breaking wave conditions eight to nine feet high and sixty feet long. These are unusually steep waves, but they could occur in certain conditions of wind, tide and sea bed. It was not found possible to overturn the model, in similar short steep waves, five to six feet high. The model test method is indicated in Figure 3-30 and shows the model placed beam into the waves, and pulled through them at the critical beam hump speed of seven knots. A 40 knot wind force was simulated by an off-set CG position and the towing methods were such that the model was subjected to snatch loads representative of gusts.

According to WRAITH (CAA JAN 77) the results showed that when the model was operated at normal turbine speeds, of 17 to 18,000 rpm, it was not possible to overturn the craft in repeated tests. Also, if the engine power was completely cut at the most critical moment, so that the side structure was buried in the water, no overturning was achieved. However, if the power was reduced from 18,000 turbine rpm to 14,000 at the critical moment, the model could be made to overturn, in approximately 1 in 15 occasions. This 1 in 15 occasions could only be made to occur, if the craft was almost exactly beam to sea, and drifting sideways at the critical speed. If the model was 20° off the beam condition, no overturning could be made to occur.

*i.e. low lift fan speed and hence low cushion air flow rate.

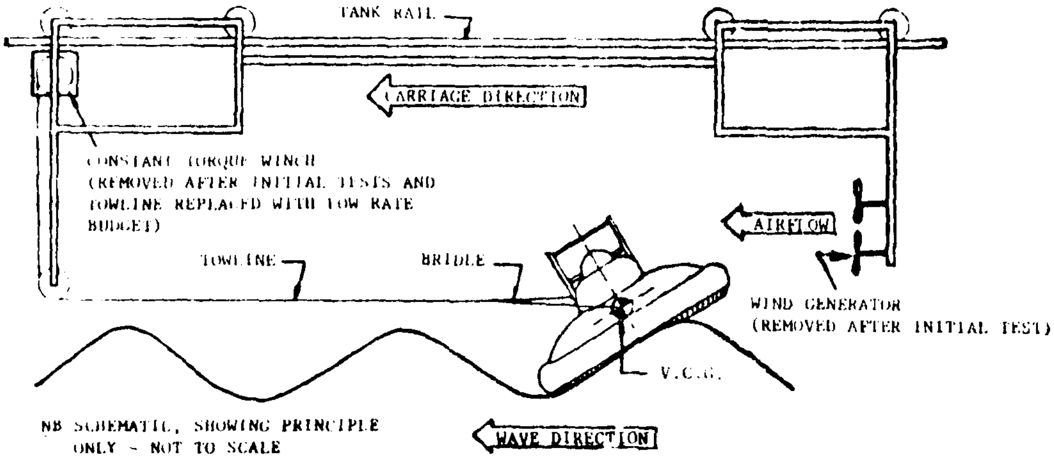


FIGURE 3-30. DIAGRAM OF BEAM TOWING RIG 1/75 SCALE MODEL 105. (CAA JAN 77)

WRAITH emphasized that these were the preliminary results of a general set of overturning model trials. Deliberately severe conditions, compatible with those observed at the time of the accident, had been chosen to find, quickly, a condition that would reproduce the over-turning. The key factor appeared to be a partial reduction of turbine speed (i.e. reduced cushion air flow rate) at a critical moment and it appeared from the model tests, that wind strength and asymmetric craft loading were quite secondary effects. Even so, overturning could only be produced occasionally.

WRAITH (CAA JAN 77) also reports on a program of model capsizing tests conducted by BHC for the British Department of Trade and Industry. The behavior of several model ACVs in calm and rough water were investigated including a model of the HD-2 with uncompartmented skirt. Results for the HD-2 are shown in Figure 3-31 which has been reproduced from the original test report (BHC MAR 73). This figure shows roll angle variation with constant beam-on (or sideways) towing speed measured over calm water with an adverse rolling moment. As noted in CAA JAN 77, the resulting curve shows a sharply defined critical-speed region around 6.5 knots where either overturning, under the model-test conditions, or severe trailing-side skirt scooping occurred with the application of only moderate adverse moments. According to CAA JAN 77 , it is not completely understood why at 6.5 knots the model is unstable yet completely stable at 0.5 knots either side of this value. It is noted, however, that wave making drag and cushion induced wave surface elevations vary very rapidly in the speed range 6 to 7 knots for the HDL model and this could severely influence the balance of skirt-contact forces and cushion restoring moments for this speed range.

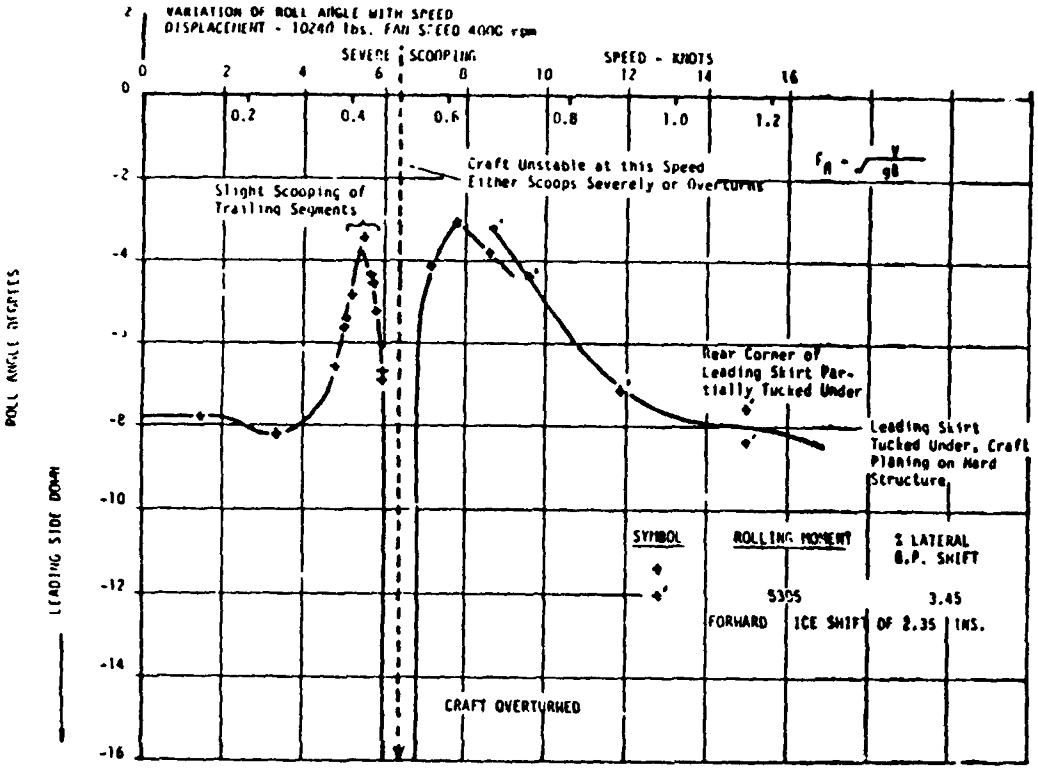


FIGURE 3-31. RESULTS OF HD-2 MODEL BEAM-ON TOWING TESTS (BHC MAR 73).

The test in beam seas indicated that when decelerating through the critical-speed region the trailing skirt segments invariably scooped and the craft never appeared likely to overturn. Thus, the combination of an effective planing structure on the HD-2 hull and skirt segment scooping, together with a relatively low skirt-depth-to-cushion-beam ratio (of 0.133) appeared to provide a reasonably safe overall craft configuration. The reason for segment scooping was not defined but it was felt to be an undesirable feature since it produces high skirt loads. Also, should the segments cease scooping at an inopportune moment, through failure of the inner ties, a dangerous roll situation might develop.

Because the CAA report of JUN 1975 is perhaps the most authoritative review of ACV capsizing which has been made available to date, the conclusions and recommendations from the study are summarized below. It is noted in CAA JUN 75 that the conclusions and recommendations are generalizations based on the quantitative data and discussions given in the text and they refer exclusively to stability; other design requirements may also need to be considered.

Conclusions (CAA JUN 75)

1. "Hovercraft like all marine craft must be considered to be capsizable even if in some cases the possibility appears to be remote. Unusual environmental conditions, damage or mishandling may put any craft unexpectedly at risk. Capsizing conditions may occur when the craft is operating on full cushion or operating in the displacement mode or in any condition in between.

2. The capsizing potential of a hovercraft should be assessed for the craft with any possible angle of yaw up to a full 180°. This is especially important for those small craft which may be deliberately maneuvered in such a manner as an aid to stopping.

3. (a) For all practical purposes a standard sequence of events can be determined for an over-water capsize from the on-cushion position:

   (i) Initially the craft is on-cushion and operating normally.

   (ii) A situation and/or a maneuver occurs causing leading skirt tuck-under.

   (iii) The hard structure of the craft makes a dynamic impact with the water surface.

   (iv) The actual capsize occurs.

   (b) Leading skirt tuck-under is the most significant factor in the sequence as a necessary, although not in itself sufficient, condition for this form of capsize.

   (c) The dynamic planing force of all relevant surfaces including deformed skirts can have an important effect in determining whether the craft will tend to right itself or tend to capsize.

   (d) As the craft impact energy is absorbed the craft may develop a high angle of heel when the normal static buoyancy stability will become predominant in determining the subsequent movement of the craft.

4. In the full floating mode the stability assessments for hovercraft are essentially the same as those for (displacement) ships.

5. A reduction in the possibility of leading skirt tuck-under may reduce the incidence of overland capsizes.

6. Not very much is currently known about the actual capsizing boundaries of some craft and especially of the margin between the warning onset of skirt tuck-under and the actual point of capsize.

7. The misuse of the controls can be the prime factor in the initiation of a capsize situation.

8. Particular attention should be paid to the mechanism of skirt tuck-under.

9. Sufficient information about wind and sea conditions is not always available to Hovercraft commanders."

Design Recommendations (CAA JUN 75)

1. The tendency for the skirt to tuck-under should be as low as practicable.

2. The vertical CG position should be as low as possible.

3. Where integral lift and propulsion systems are incorporated with a fixed pitch propeller an effective means of stopping the craft, other than by reducing engine power, is essential.

4. Craft should be designed to have hydrodynamically stabilizing structures all round. This can be arranged by means of planing surfaces for high-speed beam-on motion and by adequate buoyancy reactions for low-speed motion.

5. The possible movement of payload, passengers and equipment should be minimized to reduce the de-stabilizing moment in a capsizing situation.

6. Adequate structure and skirt drainage should be provided to avoid asymmetric water-weight moments.

7. Hull superstructure designs should be such as to avoid large de-stabilizing moments as a result of high drag forces due to water trapping appendages. The effect of system and skirt failures on the likely drag forces should also be considered.

8. The design should be such that aerodynamic upsetting moments should be minimized as far as is practicable.

9. Control ports where incorporated should be designed to minimize water entry.

10. Consideration must be given in new craft design to provision of:

    (a) adequate warning of an impending capsize

    and

    (b) an adequate margin, between the warning and the eventual capsize, to enable corrective action to be taken. The crew drills necessary should be established and scheduled in the Technical Manual."

<u>Recommendations for Further General Research (CAA JUN 75)</u>

1. It was recommended that further research be carried out not only to increase basic data and knowledge but also to enable better theoretical techniques to be formulated. Owing to diversity of craft and conditions the Committee considered it was not possible to list the recommendations for further research in anything other than a very approximate order of priority, as follows: -

   "(a) Skirt tuck-under, including the effect of local wave surface elevations and breaking waves.

   (b) Hard structure hydrodynamic stability, including the effect of local wave surface elevations and breaking waves.

   (c) Establishment of aerodynamic forces and moments at high angles of pitch and roll.

   (d) Sidewall (test) program as in Appendix 4 of CAA JUN 75.

   (e) General effect of local wave surface elevations and breaking waves on overturning.

   (f) Overland capsizes including terrain transition and shallow water effects.

   (g) Effects of skirt damage."

Model and Full Scale Testing Recommendations (CAA JUN 75)

"Model tests and full scale trials for all craft types should cover the following items where possible:

1. Model tests, where appropriate, should be carried out to establish the following basic quantities and their dependence on each other:

   (a) Wave height and steepness and applied moment below which a rough water capsize cannot normally occur.

   (b) Lift-system volumetric air flow above which a capsize cannot normally occur over the range of operating conditions and applied moments.

   (c) Effects of rate of change of cushion volume air on stability.

   Parameters such as VCG position, craft roll inertia, etc., should be maintained at the most adverse values consistent with normal actual full-scale craft conditions.

2. Model tests should check the effect of the applicable maximum design (wind) gust speed.

3. Tests and trials to explore and establish the skirt tuck-under boundaries should be established in terms of minimum lift engine RPM or its equivalent.

4. Failure cases checked during trials should include the mishandling of controls, particularly hydrodynamic rudders.

5. During trials, recordings of roll angle and differential cushion pressures, where appropriate, should be included amongst the information to establish the skirt tuck-under boundary and floating stability.

6. Model tests should include checking the effect of beam-on motion under high wind and sea conditions while in the displacement mode."

Operational Recommendations (CAA JUN 75)

1. "The following operational procedures are recommended to be incorporated in all Type Operating Manuals in order that hovercraft commanders can minimize the risk of capsize in calm water.

   (a) If possible avoid moving at yaw angles between 60° and 120°

   (b) Do not reduce cushion air if moving at these yaw angles.

   In addition while operating in rough water:

   (c) Avoid sliding sideways into or down beam seas. The craft heading should be at least 20° from the line of wave fronts.

2. Information on basic hovercraft stability and control should be compiled in a form suitable for hovercraft commanders.

3. Commander training should include the knowledge of environmental conditions recommended in Appendix 5 Part 3 of CAA JUN 75. Special efforts must be made to acquaint hovercraft commanders with the particular environmental conditions of their route.

4. Driving instruction should cover all craft and weather operating conditions, including emergency conditions beyond those for which the craft is certified for passenger service, before a full licence is granted. If necessary, the licence should be issued in stages leading to full clearance.

5. Hovercraft commanders should be subject to a regular re-assessment of their craft handling procedures during commercial services.

6. Leading skirt tuck-under which results in a plow-in when experienced during normal operations, should be a notifiable incident. The commander should also note in the craft log book any uncharacteristic behavior of the cushion system."

Requirement Recommendations (CAA JUN 75)

1. "Chapter B5-9 of the British Hovercraft Safety Requirements(BHSR) should be reviewed to ensure that adequate floating stability margins are required for the intact and selected damage cases.

2. The relevant requirements on controls and controllability in BHSR should be progressed by the CAA."

General Recommendations (CAA JUN 75)

1. "The Committee strongly recommends that data which have a relevance to craft safety should be actively circulated amongst all appropriate Hovercraft Authorities.

2. The Committee recommends that this report be made available to all interested parties at home and overseas.

3. Appendix 1 of CAA JUN 75 should be forwarded to the British Standards Institute and other authorities so that the terms and symbols can be considered for general use by the hovercraft industry.

4. The exchange of technical information throughout the industry should be encouraged.

5. Hovercraft technology is comparatively new and is subject to change. It is therefore essential that this report be regarded as relevant to the current time only and that it should be reviewed at regular intervals."

3.5 STABILITY STANDARDS FOR PLANING CRAFT

3.5.1 USCG Standards

The United States Government Code of Federal Regulation Title 46 "Shipping" containing section 74.1 (Chapter H) is the Weather (or Wind Heel) and Passenger Heel Criterion which the U.S. Coast Guard apply to all passenger vessels. For off-shore supply vessels and crew boats this is modified by application of a stability criterion (See Table 1, USCG, NO DATE) similar to Raholas (1939) following the recognition (in 1964) that G.M. limits alone were insufficient. (See also USCG "Rules and Regulations for Small Passenger Vessels (under 100 gross tons, Subchapter T, CG-323)).

It is this criterion which is currently applied to all small passenger carrying vessels in U.S. Waters including passenger carrying planing craft. It does not apply to recreational boating, (the discussion of which is outside the scope of this present study).

The wind heel criterion,formulated in the early 50's,established unit wind pressures for lakes, bays, and sound, coastwise and oceangoing vessels which thus established a heeling moment. The standard required that the metacentric height (GM) be sufficient that the vessel would not heel in excess of one-half the freeboard or 14 deg, whichever is less. The passenger heel criterion similarly required the passengers all to be placed so that the center of their weight was one sixth of the beam from the centerline of the ship, and the heel angle could not exceed that specified for the wind heel criteria. Passenger vessels also had to meet damage stability criteria, and in those days these were generally governing. If the vessel was a high-speed craft the designer routinely checked the heel during a high-speed turn, and if the vessel had weight-handling equipment he checked the heel caused by lifting weights on and off the vessel and assured himself that these heels were within acceptable limits. (NICKUM JUL 78)

The 1964 modification to the wind-heel and passenger heel criterion adopted only the righting energy part of Rahola's criterion and required that the righting energy up to the angle of maximum GZ, the angle of downflooding, or the angle 40 deg, whichever was smaller, be at least 15 deg-ft. The USCG did not adopt Rahola's minimum GZ of 0.66 ft, nor did they, for offshore supply boats, adopt the approach that the angle of GZ maximum be not less than 30 deg. When the basic Coast Guard wind heel criterion was applied this was very seldom governing. The subsequent number of casualties to offshore supply boats was much reduced. (NICKUM JUL 78)

3.5.2 Other Standards Applicable to Planing Craft

ABYC, "Safety Standards for Small Craft"

MIL-STD-1472B, "Human Engineering Criteria for Military Systems, Equipment and Facilities."

USCG, "Rules and Regulations for Uninspected Vessels, Subchapter C", CG-258

NAVSEC, NORFOLK, "Procedures Manual, Dynamic Stability Analysis for U.S. Navy Small Craft", Report No. 23095-1, January 1977.

Lloyds, "Rules and Regulations for the Construction and Classification of Wood and Composite Yachts"

Lloyds, "Provisional Rules for the Construction of Reinforced Plastic Yachts"

3.5.3 General Considerations

The above standards do not necessarily recognize,however, the special considerations of the high speeds achievable by modern day passenger carrying planing (or semi displacement) craft. For chine boats,the question of transverse stability has, over the years, been given very limited treatment. However, the fact that these vessels were always beamy with very large transverse GM's when planing, has seemed to have satisfied the test of time. Compared with other types of dynamically supported craft the planing craft is well known and has been in wide use for very many years. The principles of planing lift are well understood; a great deal of theoretical and experimental work has been devoted to the study of resistance of planing hulls and very large numbers of successful and safe planing craft have been built for military, commercial and private use. The stability of planing craft, however, is an extremely complex subject and very little analytical work has been done on this subject. One reason for this is that there has not been very much incentive. Stability problems of planing craft have, traditionally, been solved empirically and successfully by simple, practical remedies such as the use of ballast to move the center of gravity or the use of transom flaps or "shingles" to change the running trim angle. In any case,the modes of instability that do occur,during the operation of planing craft at moderate speeds,are normally rather mild and can be avoided by the operator by changing trim (by thrustline or transom-flap control), by changing speed or by moving passengers or crew. Observation of any of the nation's waterways on a weekend in the summer indicates that planing craft can suffer wide ranges of operational abuse in terms of loading, speed and turning maneuvers,without displaying undesirable, unstable tendencies.

Stability problems encountered by planing craft can be categorized as follows: -

(a) Displacement mode -

The planing craft is very often much less stable in the displacement mode than when planing. This is particularly true of the deep-vee types and much less true of multi-hull types. The Seaknife, for exmaple, which can be regarded as an extreme case of a deep-vee type is undesirably unstable when at rest. The fact that many small craft are rather prone to swamping and capsize when at rest has been the cause of many accidents.

(b) Porpoising -

The coupled pitch and heave instability known as "porpoising" is probably the most commonly experienced mode of instability encountered in planing craft. At moderate speeds it can be persistent but is usually not very severe. Once porpoising starts it will usually not die out until either the trim is changed or speed reduced. At high speeds porpoising can be extremely dangerous as it is aggravated by large aerodynamic forces and can rapidly build up until the craft leaves the water entirely, which can cause the craft to flip or can cause such severe impact loads that the craft breaks up. Such accidents are not infrequent among racing hydroplanes.

The factors governing coupled pitch and heave instability were first analyzed by Perring and Glauert 1932,using the "Routh Discriminant" approach to study the take off and landing dynamics of sea planes. For application to planing craft,several researchers have since provided useful guidelines for establishing porpoising limits. These include DAY & HAAG MAY 52, CLEMENT (63 and 66), SAVITSKY OCT 64, HSU MAY 67, PAYNE AUG 73, ANGELI APR 73 and MARTIN MAR 78.

As noted above, porpoising can lead to large aerodynamic pitch-up moments. The aerodynamic stability of a planing craft is best evaluated in a wind tunnel. Consderable discussion on this topic can be found in DU CANE 72, page 394.

(c) Transverse Stability -

Most hard chine craft are very stiff in roll when in the planing mode as a large restoring moment is generated when one side of the planing bottom is immersed further than the other. Some deep-vee types exhibited poor roll stability in initial trials but it was found that this could be remedied very simply and effectively by fitting longitudinal spray strips on the planing bottom. During turning maneuvers the V shape of most planing bottoms provides a favorable rolling moment as the craft sideslips, so that the craft will roll inwards in a turn. Occasionally, in deep-vee types coupled roll and pitch instability can occur if the forefoot digs in during a turn and causes the craft to roll outboard. The prototype Seaknife, for example, which has a very deep forefoot, was destroyed when it capsized in this way by "tripping" and rolling outboard in a turn.

Some rounded chine, round bilge or semi displacement craft have been known to exhibit a loss of roll stability with increased forward speed. In particular, SUHRBIER, 7 MAR 78,reports on a series of model tests performed for Vosper Throneycroft (UK) Limited from which the loss of metacentric height (GM) with forward speed and the effect of spray rails were investigated.

SUHRBIER, 7 MAR 78 also mentions that the well-known feature of chine boats, that they heel inwards when turning, is predominantly due to the action of the rudder, but is very likely also enhanced by their chine form. The Vosper Thorneycroft TENACITY with a rather beamy round-bilge form, heeled outwards 2 or 3° when turning at full rudder. TENACITY had an extremely high value of transverse GM, so this is perhaps not surprising. It is a fact, however, that if one applies the accepted formula as given by Sarchin and Goldberg 62 for calculating angle of heel when turning to TENACITY, the calculated angle is four times the measured angle at high speeds. This is mentioned by Suhrbier only to illustrate how very wrong one can sometimes be in using, for small, fast vessels, methods of calculation or criteria which are accepted for slower and more normal craft. Naturally, the criteria mentioned would apply at least approximately to such ships when proceeding at normal cruising speeds and not at extreme speeds. It is fortunate that the error is on the safe side, and that conventional methods over-estimate the angle of heel when turning at high speeds. At the moment the only design guidance that can be offered is empirical, and it is a subject which clearly would repay some analytical if not theoretical study.

(d) Directional Stability -

The directional stability of planing craft is usually very good in calm water. The center of hydrodynamic lateral effort is well aft of the c.g. so that the craft is statically stable in yaw and does not require the continuous adjustments of the helm that are characteristic of displacement ships.

According to RINA MAY 78 fast patrol boats are, however, at some risk from broaching to in following waves from the effect of excessive bow immersion which reduces directional stability of the hull and simultaneously the effectiveness of the rudder. HEATHER MAR 78, in fact, shows the results of model experiments which indicate risk in steep following seas where the Froude number is greater than 0.23. See Figure 3-32.

RINA MAY 78, also states that course-keeping problems at high speeds may be overcome by an increase in roll stiffness. Many semi-displacement craft experience a reduction of roll stiffness at high speeds, particularly at Froude numbers above 0.6. Dangerous situations can arise if helm is applied in an attempt to correct yawing motion caused by heel; the rudder forces produced may increase roll and thus aggravate the stability problem.

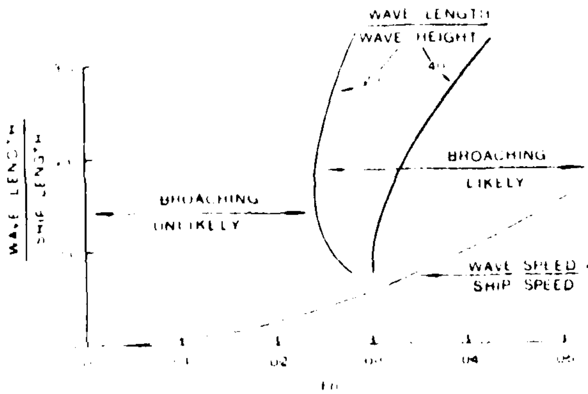


FIGURE 3-32. MINIMUM SPEED LIMIT FOR ACCELERATION TO SPEED IN FOLLOWING SEAS AND PROBABLE BROACHING-TO REGEMES FOR FAST PATROL CRAFT. (RINA MAY 78)

(e) Stability in a Seaway -

The same geometric characteristics that cause a planing craft to have very stable characteristics in calm water cause it to have a rough ride in waves. As the craft moves through waves the area of the planing bottom in contact with the water changes rapidly and the planing force changes in proportion. The resulting accelerations and motions get rapidly more severe as speed and wave height increase and usually result in the operator reducing speed until a more comfortable situation is obtained. This usually means that the planing craft only encounters severe sea states in the displacement condition. The planing craft in the displacement condition in a seaway has several disadvantages compared with a displacement ship:

- The large areas of superstructure often present may cause large rolling moments due to windage and large angles of roll due to high roll inertia.

- The shallow draft may interact with the waves to cause unusual variations in waterplane area and hence metacentric height.

- The shallow draft may also result in directional instability in following seas leading to broaching (as mentioned earlier).

- The wide square transom and open cockpit areas may be prone to swamping in following seas.

Only in very unusual circumstances, such as in ocean racing, will planing speeds be maintained in rough water. Under these conditions very high accelerations are experienced and structural damage and crew injuries are not uncommon.

4. CRAFT HAZARD CLASSIFICATION

Because of the high-speed capability of dynamically supported craft, combined with their generally higher responsiveness to control action, there exists, for these craft, particular hazards to safe operation which are not generally of concern to conventional displacement craft. Additionally, many of the hazards which exist for displacement craft will also apply equally to dynamically supported craft.

Table 4-1 presents a list of hazards which are considered applicable to dynamically supported craft. (These are defined in more detail later.) A hazard, in this case, is a situation of craft state and operating environment which is known to have the potential of causing either property damage, personnel injury or loss of life.

The probability of the simultaneous occurrence of all of these hazards is, of course, very remote. At the same time, certain combination of hazards may well occur simultaneously and may provide design conditions for some forms of craft and conditions of operation.

CLEARY MAR 75, in his general discussion of Marine Stability Criteria, presents a convenient classification in which the term FORM is used to classify the type of craft; the term SERVICE is used to group the type of cargo and variations in the planned or inadvertent loading to be expected of the craft or to which the craft may be subjected and the term EXPOSURE is used to group the sea or weather related forces that the craft is expected to encounter. In addition, CLEARY MAR 75 suggests that each potential hazard should be examined to clearly distinguish whether the event is a surprise for which the crew may not be prepared (in which case the craft must save itself) or whether the event is one for which the crew is readily prepared. These classifications are included in Table 4-1 and can be used to help determine the likelihood of the combined application of certain hazards.

TABLE 4-1. LIST AND CLASSIFICATION OF POTENTIAL OPERATIONAL HAZARDS FOR DYNAMICALLY SUPPORTED CRAFT.

	OPERATIONAL HAZARDS	TYPE	CREW AWARENESS
1	Cargo-loading misalignment	SERVICE	P or S
2	Crowding of passengers to one side	SERVICE	S
3	Inadvertent cargo shifting	SERVICE	S
4	Lifting heavy weights	SERVICE	P
5	Retracting foils	SERVICE	P
6	Free-surface effect	SERVICE	P
7	Top-side icing	EXPOSURE	P or S
8	High-speed turns	SERVICE	P or S
9	Inadvertent control-force action	SERVICE	S
10	Severe wind strength	EXPOSURE	P or S
11	Severe sea state	EXPOSURE	P or S
12	Towing	SERVICE	P

P: Prepared for
S: Surprise

In Table 4-2, for example, the types of unstable behavior that have been known to occur with dynamically supported craft are listed. The list includes an *identification of the primary and secondary modes of craft motion involved* in each case and shows for which craft type the mode of instability applies.

TABLE 4-2. CLASSIFICATION OF CRAFT TYPES AND TYPES OF INSTABILITY.

	TYPES OF INSTABILITY[1]				HAZARD IDENTIFICATION[8] — TYPES OF CRAFT[2]: Planing Craft (· Mono Hulls · Multi-Hulls)	Hydrofoil Craft (· Surface Piercing Foils · Fully Submerged Foils)	Surface Effect Ships (· Full Length Sidehulls · Partial Length Sidehulls)	Air Cushion Vehicles (· Bag-Finger Skirt · Multi-Cell Skirt)	Criticality
	DESCRIPTION	MODE	PRIMARY D.O.F.	SECONDARY D.O.F.					
	PITCH								
A	Plow-In	Divergent	θ	ZX	✓	✓	✓	✓	I
B	Porpoising	Oscillatory[7]	θ	Z	✓	-	-	-	I
C	Pitch-Click[3]	Oscillatory	θ	-	-	-	✓	✓	N
D	Aero Pitch-Up[4]	Divergent	θ	Z	✓	-	-	-	L
E	Pitch-Pole	Divergent	θ	ZX	✓	-	-		L
	YAW								
F	Broaching to	Divergent	ψ	Y	✓	✓	✓	✓	I
G	Fish Tailing	Oscillatory	ψ	Y	-	-	-	-	N
	ROLL								
H	Tripping[5]	Divergent	ϕ	ψ,Y	✓	✓	✓	✓	L
I	Click-Stop	Oscillatory	ϕ	-	-	-	-	-	N
J	Dutch-Roll	Oscillatory	ϕ	ψ	-	-	-	-	N
	HEAVE								
K	Foil Broaching	Divergent	Z	θ,ϕ	-	✓	-	-	I
L	Bottom Slamming	Oscillatory	Z	θ	✓	✓	✓	✓	I
M	Heave Limit Cycle	Oscillatory	Z	-	-	-	✓	✓	I
	SURGE								
N	Loss of Dyn. Lift[6]	Divergent	X	Z,θ	-	✓	-	-	I
O	Loss of Dyn. Lift[6]	Oscillatory	X	Z,θ	-	✓	-	-	I
P	SWAY/SIDE SLIP	Divergent	Y		-	-	-	-	N

NOTES: D.O.F.: Degree of Freedom
θ: Pitch
ψ: Yaw
ϕ: Roll
Z: Heave
X: Surge
Y: Sway

1. Behavior which is undesirable or which has been known to cause or is likely to cause property damage, personnel injury, or loss of life.
2. Craft types and their various configurations.
3. Bow-down excursions due to intermittent skirt tuck-under.
4. Craft Pitch-up at high speed due to aerodynamic instability.
5. Sudden increase in side drag with craft progressing at high-sideslip or beam-on.
6. Loss of lift on foil in following seas.
7. All oscillatory modes might lead to divergent-oscillatory mode.
8. See Table 4-1 for operational hazards.

I: personal injury and/or property damage
L: loss of life
N: Undesirable but generally safe behavior

The extent to which each class of craft is susceptible to a common hazard would, of course, be dependent on many detail design variables as discussed in Chapter 5. The degree of importance associated with each type of instability is indicated (to some extent) by the far right-hand column of Table 4-2. This shows where the type of instability can be regarded as undesirable but generally safe, where personnel injury and/or property (i.e. craft) damage can occur, and where loss of life is potentially at stake.

It should be appreciated that some forms of unstable craft behavior can lead to other, perhaps more critical, (less safe) behavior. A classical example for ACVs or SES is the "so-called" pitch-click instability, listed in line item C of Table 4-2 which results from a lack of pitch static stability for small pitch excursions about nominal trim. This type of behavior although not exhibited by all ACVs or SESs is not particularly uncommon and although undesirable from a performance standpoint, is fairly benign. If excessive, however, (perhaps due to the existance of other disturbing forces) an exaggerated state of leading-skirt tuck under can occur leading to excessive pitch down and eventual plow-in causing hard structure contact with the water (as listed on line item A of Table 4-2). Plow-in, itself, is also not a particularly uncommon or necessarily dangerous situation for an ACV or SES in the hands of an experienced operating crew. If, however, it occurs at very high speed, (where, incidentally, it is most likely to occur) and, for some reason, no action is taken by the crew to minimize its severity, the process of plow-in has the potential of subjecting the craft to very high rates of deceleration and uncontrolled yaw, which in turn can eventually result in high-speed, sideways (beam-on) motion, side-skirt tuck under, hull tripping and a capsize in roll (line item H of Table 4-2). Such events have occurred on several occasions.

Note that the possibility of pitch-click behavior, line item C for an ACV or SES, can be accentuated (although not often) by hazard items 1, 3 and 6 from Table 4-1. In turn, plow-in can be accentuated by hazard items 1, 3, 7 and 9 of Table 4-1 and tripping, leading to capsize in roll, can be accentautéd by hazard items 1, 2, 3 and 6 through 11. Thus, the only hazard items which are excluded from affecting this scenario are items 4, 5 and 12 which occur only in the displacement mode of operation. This, of course, is a rather oversimplified analysis. It does, however, provide a starting point for assessing the possible combination of the various operational hazards.

Note also that capsizing in roll, for an SES or ACV need not result only as a consequence of severe plow-in. Operation in severe beam seas and winds have also been known to cause capsize.

In the following subchapters the various hazards and modes of instability to which dynamically supported craft can be subjected are defined. Included is an identification of those hazards which can reasonably be combined for the purpose of developing stability standards for each possible mode of instability.

4.1 CRAFT HAZARD DEFINITION AND COMBINATION

An identification of the hazards which have a reasonable probability of occurring simultaneously is given in Table 4-3. An explanation of each hazard and the rationale for their combination in certain cases is discussed below:

TABLE 4-3. IDENTIFICATION OF HAZARDS WHICH HAVE A REASONABLE PROBABILITY OF OCCURRING SIMULTANEOUSLY

* DISPLACEMENT MODE ONLY
** COLD WEATHER SERVICE ONLY

		1 CARGO LOADING GROSS MISALIGNMENT	2 CROWDING OF PASSENGERS TO ONE SIDE	3 INADVERTENT CARGO SHIFTING	4 LIFTING HEAVY WEIGHTS*	5 RETRACTING FOILS*	6 FREE SURFACE EFFECTS	7 TOP SIDE ICING**	8 HIGH SPEED TURNS	9 INADVERTENT CONTROL FORCE ACTION	10 SEVERE WIND STRENGTH	11 SEVERE SEA STATE	12 TOWING
1	CARGO-LOADING GROSS MISALIGNMENT		-	-	*✓	-	✓	✓	-	-	✓	-	*✓
2	CROWDING OF PASSENGERS TO ONE SIDE			-	-	*✓	✓		-	-	✓	-	*✓
3	INADVERTENT CARGO SHIFTING				*✓	*✓	✓	✓	-	✓	✓	✓	*✓
4	LIFTING HEAVY WEIGHTS*					-	✓		-	-	✓	✓	-
5	RETRACTING FOILS*						✓	*✓	-	-	*✓	*✓	*✓
6	FREE-SURFACE EFFECTS							✓	✓	✓	✓	✓	✓
7	TOP-SIDE ICING**								-	✓	✓	✓	*✓
8	HIGH-SPEED TURNS									✓	-	-	-
9	INADVERTENT CONTROL-FORCE ACTION										✓	✓	*✓
10	SEVERE WIND STRENGTH											✓	*✓
11	SEVERE SEA STATE												*✓
12	TOWING												

(1) Cargo Loading Misalignments

Cargo elements with inprecisely known weights can be loaded in such a way that very significant departures from normal craft C.G. location can be caused. A gross misalignment of craft C.G. will, however, assuredly become apparent to the crew (of a dynamically supported craft) soon after (if not before) underway operations commence. The crew would then presumably realign the cargo (which may involve returning to base) or they would continue with extreme care not to subject the craft to the most severe adverse control force actions, high-speed turns or operation in the most severe sea states for which the craft is designed.

It is further assumed that a cargo misalignment hazard applies to cargo carrying craft only. If a cargo carrying craft also carries passengers it is assumed that the crew would be aware of the misalignment and all passengers would then be instructed to remain in their seats and to wear seat belts during underway operations. Similarly, the inadvertent shifting of cargo which could otherwise result from craft rapid deceleration due to sudden control force actions or operation in the most severe sea conditions is also considered unlikely. Note that the term "most severe" is used above to imply the maximum conditions which the craft is designed to encounter. This includes the maximum sea state-speed envelope and maximum control forces and moments available. Although the effect of high-speed turns, inadvertent control-force action and severe sea states are shown as being excluded from combining with cargo loading misalignment in Table 4-3, some less severe combination of these hazards would appear to be necessary. (No attempt is made here to establish such a combination since this would be the subject of the subsequent Phase II of the Program.)

It is considered important, however, to include the most severe wind speeds in combination with cargo loading misalignment. High wind squalls can occur very suddenly and in many instances without warning, as compared to the time required for sea conditions to change appreciably. Five items, therefore, remain for combination with cargo loading misalignment (as shown in Table 4-3), two of which apply only in the displacement mode of operation and one of which applies only to very cold weather service.

(2) Crowding of Passengers to One Side

The heeling moment due to passengers crowding to one side of a craft can be estimated with respect to the space and deck plan of the craft. Such an event is not expected to occur in the most severe sea state, during the most severe high-speed turn nor in combination with severe cargo shifting. It can however occur both in the dynamically supported and displacement modes of operation.

(3) Inadvertent Cargo Shifting

Most often, cargo will be tied down when the craft is underway, particularly if heavy seas are expected. In the most severe seas for which the craft is designed, cargo may, however, shift and cause a large destabilizing moment.

(4) Lifting Heavy Weights

Loading and unloading cargo at sea would be confined to displacement mode operation and would most likely be performed in connection with offshore crew and supply-boat service. Operation with inadvertent off-set load conditions combined with beam seas and strong wind gusts would require consideration.

(5) Retracting Foils

This would apply only to hydrofoil craft in the displacement mode. The effect of changing C.G. height and craft windage conditions due to raising the foil system would be considered in combination with items shown in Table 4-3.

(6) Free-Surface Effects

The reduction of stability due to the free-surface effect of fuel and in particular the free-surface of entrapped water on deck or within cargo spaces due to rough-water operation can be a significant hazard for some craft types.

(7) Top-Side Icing

Superstructure icing during extreme cold-weather service, can cause a significant change in C.G. location particularly if icing is assymetric. The ACV and SES could be particularly prone to assymetric icing conditions due to cushion-generated spray in beam winds.

(8) High-Speed Turns

During collision-avoidance maneuvers at high forward speeds, large side-slip angles can be expected in combination with large control-force actions. This, combined with other possible hazards shown in Table 4-3, can subject a craft to a significant destabilizing condition in roll.

(9) Inadvertent Control-Force Action

Although it is usually expected that the use of the craft controls is such as to minimize potential hazards, most accidents with dynamically supported craft have occurred as a result of inappropriate control action. Because of the high speeds and/or high thrust levels available, dynamically supported craft generally exhibit a very large control-force-to-gross-weight ratio relative to conventional ships. Thus, the consideration of destabilizing forces and moments from inappropriate action of the controls should take a higher priority for dynamically supported craft than is normally the case with conventional craft.

(10) Severe Wind Strength

High steady or gusting winds can be a significant hazard particularly with craft having high freeboard (or extensive superstructures) which tends to be the case for most dynamically supported craft, at least when in the non-displacement mode. Beam winds, combined with rolling in severe beam seas and when combined with the other possible hazards shown in Table 4-3, are of particular concern. Combined quartering winds and severe wave action can also be of concern.

(11) Severe Sea State

Apart from the natural concern of capsizing in combined severe beam seas and wind, craft operation at the extremes of the design sea state-speed envelope can, for high-speed craft, result in relatively hazardous bottom slamming. Although it would be expected that the crew would reduce speed to minimize severe slamming it is possible that the random nature of encountered waves could take the crew by surprise, and result in structural damage or injury to personnel on board.

(12) Towing

The recovery of a disabled craft in adverse weather may involve towing. Other than in the case, perhaps, of an ACV this would be accomplished with the craft in the displacement mode. With severe wave action and winds, the management of tow lines would be severely hampered and could result in the application of significant destabilizing moments particularly if the assisting craft or ship is much larger than the disabled craft.

4.2 TYPES OF INSTABILITY

Table 4-2 provides a list of known types of instability which have been exhibited by dynamically supported craft. Some apply to only one type of craft; others apply to all types. As was noted in the previous subchapter, only certain types of instability can be regarded as serious, that is, having the potential of directly causing personnel injury, property damage or loss of life. It is these types of instability which are briefly defined below* along with the service imposed operating hazards which are known to have an influence on their initiation. A comparison of the critical instability types and corresponding service hazards is given in Table 4-4.

4.2.1 Plow-In, Type A

Plow-in is an unstable pitch-down event which can (and has) occurred for both SES and ACVs. It occurs when the bow skirt of an ACV or bow seal of an SES becomes excessively immersed because of some out-of trim moment causing a large (e.g.-3°) bow down attitude. Plow-in occurs when the increased hydrodynamic drag which results from the additional skirt contact is sufficient to cause a state of excessive skirt tuck-under, which in turn results in a loss in pitch-up restoring moment and further pitch-down motion. Eventually, hard-structure contact with the water can occur if no corrective action is taken by the crew. This can then lead to a high rate of craft deceleration and, if the design is such that directional control cannot be maintained, high sideslip angles can result and the craft can become in danger of running broadside-on and eventually overturning in roll.

Plow-in events have normally corresponded to operation at high speed, with forward craft C.G. locations and have been most likely to occur at reduced cushion air-flow rate. The on-set of such events have been typically characterized by what the craft operators have referred to as a skirt nibbling (deceleration) sensation (i.e. some forewarning has usually been present). Resultant craft decelerations and bow down motions have been typically of the order of -0.05g and -3 degrees, respectively. Usually, for an ACV, normal pitch trim is recovered following a reduction in air-propeller thrust.

* More indepth discussions of instability types can be found in Appendix A "State of the Art Review of Craft Stability" of Volume I - Master Report, prepared in support of the Background Study for this program.

TABLE 4-4. CRITICAL TYPES OF INSTABILITY EXHIBITED BY DYNAMICALLY SUPPORTED CRAFT IN COMPARISON WITH CORRESPONDING SERVICE HAZARDS.

	INSTABILITY TYPE		PorS	S	S	P	P	P	PorS	PorS	S	PorS	PorS	P	CRAFT TYPE
A	PLOW-IN	I	✓		✓				✓		✓		✓		SES/ACV
B	PORPOISING	I	✓		✓			✓	✓		✓				PLANING C
D	AERO PITCH-UP	L	✓		✓						✓	✓	✓		PLANING C
E	PITCH POLE	L	✓		✓						✓		✓		"
F	BROACHING TO	I	✓	✓	✓						✓	✓	✓		ALL
H	TRIPPING AND/OR ROLL CAPSIZE	L	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	ALL
K	FOIL BROACH	I	✓	✓	✓						✓		✓		HYDROFOIL
L	BOTTOM SLAMMING	I	✓		✓						✓		✓		ALL
M	HEAVE LIMIT CYCLE	I													ACV/SES
N	LOSS OF DYN.LIFT	I											✓		HYDROFOIL
O	LOSS DYN. LIFT	I											✓		"
			1	2	3	4	5	6	7	8	9	10	11	12	

SERVICE HAZARD

	Service Hazard	
1	CARGO-LOADING GROSS MISALIGNMENT	PorS
2	CROWDING OF PASSENGERS TO ONE SIDE	S
3	INADVERTENT CARGO SHIFTING	S
4	LIFTING HEAVY WEIGHTS*	P
5	RETRACTING FOILS*	P
6	FREE-SURFACE EFFECTS	P
7	TOP-SIDE ICING	PorS
8	HIGH-SPEED TURNS	PorS
9	INADVERTENT CONTROL-FORCE ACTION	S
10	SEVERE WIND STRENGTH	PorS
11	SEVERE SEA STATE	PorS
12	TOWING*	P

P: PREPARED
S: SURPRISED
I: PERSONNEL INJURY
L: LOSS OF LIFE
*: DISPLACEMENT MODE

In reference to Table 4-4 it is known, or expected, that plow-in can be initiated or can be aggravated by several service hazards: -

1. Cargo loading misalignment
3. Inadvertent cargo shift
7. Top-side icing
9. Inadvertent Control Action
11. Severe sea state*

Note that the term plow-in was coined exclusively to describe an ACV or SES phenomena. In more conventional terms the word "rooting" has been used to describe an event when any craft buries its bow which, if it occurs, is usually when running in following seas and the craft or ship attempts to negotiate a wave crest following a pitch-down motion caused by a previous wave. (It is the counterpart of pooping when a wave is taken over the stern.) Thus, the ACV/SES term "Plow-in", could be more loosely used to encompass a rooting event for other dynamically supported craft and which would also be influenced by the service hazards 1, 3, 6, 9 and 11 (Table 4-4) defined above. See also the possible consequence of planing-craft porpoising discussed below.

4.2.2 Porpoising, Type B

Porpoising is defined as the oscillatory motion of a planing craft in combined pitch and heave. It occurs with craft planing at high speed in smooth water, and if severe enough, can result in craft structural damage, or personnel injury. It may also result in diving (tripping over the bow) when the low trim angles, reached in the lower part of the porpoising cycle causes the bow to dig in. (SAVITSKY OCT 64). This type of instability is known to have been responsible for many serious boating accidents. According to DU CANE 72, single or multi-stepped hull forms are particularly prone to porpoising. Equally so are the stepless or so-called hard-chine boats if driven at sufficient speed. Service hazards which can aggravate or initiate porpoising include those previously identified for plow-in with the exception of severe sea states. It is expected also to be aggravated, in some instances, by unstable tendencies induced form free-surface effects. (See Table 4-4).**

4.2.3 Aero Pitch-Up, Type D

Particularly serious accidents have occurred with light displacement, very high-speed craft when, as a result of some pitch-up disturbance sufficient aerodynamic lift (or bow-up moment) is generated to cause the craft to become airborne and then either to flip over or to slam back onto the water surface. Such an event can be initiated at very high speeds either as a result of porpoising, encountering a wake, when operating in waves, when encountering a sudden gusting headwind, or it can occur as a result of inappropriate pitch trim control.**

* Many plow-in events have occurred in calm water.

**See DU CANE 72 page 389 for discussion of types of testing necessary to determine propoising and Aero Pitch-Up boundaries.

4.2.4 Pitch-Pole, Type E

Although a relatively uncommon event, high speed craft have been known to capsize in a purely pitch-down (ie pitch-over) motion resulting from burying the bow. Service hazards likely to aid in initiating such an event include items 1, 3, 9 and 11 shown in Table 4-4.

4.2.5 Broaching-To, Type F

This is an event in which a craft is suddenly and unintentionally thrown or caused to turn, broadside to its original direction of motion. This can result from wave (or surf) action or inadvertent control-force action and can be aggravated by other service hazards listed in Table 4-4. It results from a state of momentary loss in directional stability which is not, or cannot, be counteracted by available directional-control forces. Broaching-to is most likely to occur in severe following seas, when the craft runs down the face of one wave and burys its bow into the next wave. The craft speed will then be reduced and an overtaking wave will lift the stern high, to bury the bow more and to cause the stern to "break-away" and overtake the bow which in turn can cause a dangerous heel outwards due to the craft turning round on the down slope of the wave. Many serious accidents have occurred (DE CANE 62) with high speed craft as a result of this type of instability.

4.2.6 Tripping and/or Roll Capsize, Type H

Most capsizing events for dynamically supported craft have occurred with the craft capsizing in roll. This has most often resulted from either operation in severe beam winds and waves, hull tripping due to high sideslip operation or as a result of (or in combination with) the action of excessive and inappropriate control action. Such events can result from a chain of events initiated by some other form of instability as already discussed above. Roll capsize has been known to occur in both displacement and non-displacement modes of operation and can be aggravated or initiated by all the service hazards listed on Table 4-4. It is anticipated, however, that not all the service hazards listed in Table 4-4 would apply simultaneously at their most severe (off-design) condition .

4.2.7 Foil Broaching, Type K

This generally applies only to hydrofoil craft although some types of SES may employ foils upon which stability is to some extent dependent. Broaching is the condition which occurs when the foil breaks the water surface and loses lift. It most often occurs in severe sea states but can also occur with inadvertent control-force action or as a result of a severely tight maneuver. Other factors effecting broach are indicated in Table 4-4.

In severe seas a hydrofoil craft may alternately plow through the wave crest and broach the foils in the wave troughs, either of which constitutes a loss of heave and pitch stability (and/or roll stability if the broaching is assymetric). Wave cresting produces impact loads on the hull, for which it must be designed,

but otherwise only discomfort for crew and passengers. Broaching generally occurs only with the forward foil(s) and results in an immediate, almost complete loss of lift. The bow falls and the foil reenters the water. Full lift is not regained immediately, because the reentering foil remains ventilated to the atmosphere for some time, and the hull almost invariably slams into the next wave. Foilborne operation is usually regained after the next wave passes but, with increasing sea severity, a point is reached where the loss of speed due to post-broach slamming is too great and flight must be abandoned. This constitutes, of course, an overpowering instability in surge.

The scenario described above is typical of submerged-foil craft with a canard foil planform. Hydrofoils with an airplane configuration almost invariably encounter asymmetrical broaching with the result that a rolling moment is induced. Considerable roll may develop before lift is recovered on the broached foil and may persist until the hull slams in.

We do not know the extent to which forward-foil broaching is encountered on ships with surface-piercing foils. Since the bow has a greater tendency to lift in response to an approaching wave crest than that of a fully submerged foil craft, there could be a greater tendency to broaching. On the other hand, since speed would normally be lower in heavy seas, the foil may be submerged deeply enough to obviate the problem.

4.2.8 Bottom Slamming, Type L

The probability of (and severity of) bottom slamming will increase, with all dynamically supported craft, as forward speed and the height of encountered waves is increased. Bottom slamming is usually of greatest concern to the structural designer, and emphasis in recent years has been in the application of extreme value statistics to the assessment of ultimate design pressures and loads. Although the crew of a craft will undoubtedly reduce speed when slamming becomes uncomfortable, unexpected severe bottom impacts have been known to occur because of the random nature of the sea, and these have, in the past, caused injury and craft damage. Service hazards which increase the probability of casuality from bottom slamming are indicated in Figure 4-4.

4.2.9 Heave Limit Cycle, Type M

This unique SES and ACV unstable behavior, caused by the interaction of the air supply characteristic and the rate of change of cushion air leakage from the cushion, has been observed on a number of craft. Although high oscillatory peak heave accelerations of limited amplitude (of up to 1g on the SES 100A) have been recorded on occasions it is perhaps the least dangerous type of instability for ACVs and SES discussed in this chapter. For an ACV, this unstable heave motion is accentuated (and complicated) by a corresponding vertical vibration of the flexible skirt. For an SES, it occurs in near calm water when running at high speed, near minimum sidehull immersion and at the optimum trim for minimum drag. For an amphibious ACV it occurs most readily when hovering over smooth level land. In all cases it is most likely to occur when the rate of change of cushion-air leakage with heave motion is maximized by operating close to level trim over smooth land or water. It can be stopped in operation by reducing cushion flow rate or operating in an out-of-trim condition. It is minimized (and in most cases prevented) in the design stage by the correct choice of fan characteristics and by including constraints within the skirt system to minimize the participation of skirt vibration, commonly referred to as skirt bounce. It is not aggravated by any of the service hazards listed in Table 4-4.

4.2.10 Loss of Dynamic Lift, Types N and O

This is a problem for hydrofoil craft and is a circumstance leading to surge instability involving foilborne operation in following seas which are typically being overtaken. Climbing the back of the wave, with the water running away from the craft, can so far reduce the relative flow velocity over the foils that insufficient lift is obtainable and the ship settles onto her hull. This is more of a problem for surface piercing foil ships than for submerged foils with lift control, because compensation for the loss of flow velocity cannot be obtained. In any event it is not considered to present any serious hazard and is effected by only the severe sea state service hazard as shown in Table 4-4. It is the least serious type of instability for hydrofoil craft discussed in this chapter although, if excessive, its existence may lead to the more serious types craft behavior discussed previously.

5. CRAFT CLASSIFICATION

The classification of craft types for each major category is presented in this chapter to provide visibility on the variety of hull shapes, control techniques, propulsion methods and lift systems that will be considered for uniform application of stability standards.

5.1 CLASSIFICATION OF AIR-CUSHION VEHICLES

Air-cushion vehicles are distinguished from surface-effect ships by the absence of side hulls. The classification recognizes differences in skirt design, hull shape, appendages, and propulsion system.

(1) Skirt Design

1.1 Loop segment

1.2 Bag finger with stability trunks

1.3 Multicell

1.4 Pericell

(2) Hull Shape

2.1 Planing bottom deadrise

2.2 Open bottom bag feed ducts

(3) Appendages

3.1 Airfoil directional stabilizers

3.2 Aerodynamic rudders

3.3 Aerodynamic pitch stabilizers

3.4 Hydrodynamic maneuvering control rods

(4) Propulsion Systems

4.1 Fixed airscrews (open and shrouded)

4.2 Steerable airscrews

4.3 Air jets

4.4 Marine screws

5.2 CLASSIFICATION OF SURFACE EFFECT SHIPS

SES have been classified according to:

Hull (hard-structure) shape

Seal type and configuration

Appendages

Propulsion System

(1) Hull Shape

1.1 High-deadrise side hull (very little planing lift contribution)

1.2 Low-deadrise side hull (substantial planing lift contribution)

1.3 Full-length side hull

1.4 Partial-length side hull

(2) Seal Type and Configuration

1.1 Wrap-around type bow seal

1.2 Two-dimensional bow seal

1.3 Bag and finger seal

1.4 Planer seal

(3) Appendages

1.1 Skegs

1.2 Rudders

1.3 Turning Skegs

1.4 Bow stabilizers (fixed or movable)

(4) Propulsion System

1.1 Water jets

1.2 Water propellers

1.3 Air propellers

5.3 CLASSIFICATION OF HYDROFOILS

(1) Planform

1.1 Longitudinal area distribution

a. Conventional (airplane)

b. Tandem

c. Canard

1.2 Transverse area distribution

a. Split

b. Non-split (continuous)

(2) Foil Submergence

2.1 Surface Piercing

a. V-foils

b. V ladder

c. Ladder

2.2 Fully submerged

2.3 Hybrid

(3) Foil Flow Regime

3.1 Fully wetted (sub-cavitating)

3.2 Supercavitating or superventilated

(4) Stability Mechanism

4.1 Surface effect

4.2 Area variation (surface piercing)

4.3 Movable control surfaces

4.4 Hybrid

(5) Control System

5.1 Sensing

a. Mechanical

b. Electro-Mechanical

c. Other

5.2 Signal processing

5.3 Actuation

a. Mechanical

b. Pneumatic

c. Electro-Hydraulic

(6) Propulsion System

6.1 Water jet

6.2 Water propellers

Z drive

V drive

5.4 CLASSIFICATION OF PLANING CRAFT

Planing craft have been classified according to:

Hull shape

Static appendages (but may be adjustable)

Control appendages

Propulsion

(1) Hull Shape

1.1 Hard chine

1.2 Deep vee

1.3 Inverted V

1.4 Flat bottom

1.5 Round bottom

1.6 Stepped + dynaplane

1.7 Multihull

(2) Static Appendages

2.1 Transom Flaps

2.2 Spray Rails

2.3 Sponsons

2.4 Skegs

2.5 Bilge Keels

(3) Control Appendages

3.1 Rudders

3.2 Water-Jet Deflectors

3.3 Outboard Engine Skegs

(4) Propulsion

4.1 Outboard Engine

4.2 Inboard-Outboard Engine

4.3 Inboard engine

4.4 Water jets

4.5 Screw propeller

4.6 Multiple units of above

6. STABILITY STANDARD CLASSIFICATION

Chapter 3 of this report, reviewed the various stability criteria upon which standards have been based for regulating or for judging the safety of both displacement and non-displacement craft. It was noted that, so far, no widely accepted stability standards had been developed for advanced marine craft operating in the dynamically supported mode. In fact, there even existed very little specific guidance for the safe design of such craft except perhaps in the case of the fully-submerged hydrofoil craft. It appeared, however that,although diverse in application,the various approaches which had been developed could fall within one of six possible general categories. In this present chapter these basic six general approaches to the formulation of stability standards are identified and then classified according to their applicability to each class of dynamically supported craft considered in the study.

6.1 CATEGORIES OF APPROACH TO STANDARD FORMULATION

Six basic categories of approach to the formulation of stability standards have been identified. They are defined as follows:

(1) Minimum Initial Stiffness Limits -

- Metacentric Height for Pitch & Roll
- C.P. Shift per degree for Pitch & Roll

(2) Minimum Restoring Force & Moment Limits -

Minimum acceptable restoring force & moment (or moment arm) and corresponding translational or angular displacement limits.

(3) Static and Dynamic Stability Righting-Arm Curves -

Comparison of righting-arm and destabilizing-arm curves with limits placed on selected area ratios including the work done to resist capsize.

(4a) Elementary Dynamic Simulation -

Limits placed on extent of rigid-body angular rotation and translation displacement and on rates of rotation and displacement as observed from a reduced degree-of-freedom mathematical representation of craft subjected to specified hazards.

(4b) 6- Degree-Of-Freedom (DOF) Rigid-Body Simulation -

Limits set as in 4a above but with motions determined form a complete, nonlinear, time-domain simulation of craft rigid-body motion in 6-DOF.

(5) Model Tests -

Limits set as in 4a bove but with motions determined from sub-scale model tests of complete craft.

(6) Full-Scale Test & Trials -

Limits set as in 4a above but with motions determined from full-scale tests.

6.1.1 Minimum Acceptable Initial Stiffness

This is defined as the rate of change of roll or pitch restoring moment with respect to a change in ship angle of heel or trim. In classical naval architecture terms it is determined by the transverse or longitudinal metacentric height (GM) as calculated or measured in calm water for a small (± 2° or so) change in heel or trim about the still-water equilbrium condition. For displacement ships minimum acceptable values of GM are usually quoted in conjunction with a statement defining the minimum acceptable freeboard.

For SES or ACVs, in the non-displacement mode, recommended minimum acceptable levels of initial stiffness are usually quoted in terms of the percentage shift in the center of cushion pressure per degree change in pitch or roll. See chapter 3.4.1 for definition and relationship to GM.

Acceptable stiffness values have historically been assessed from practical full-scale operational experience. For displacement craft, values have been based on the statistical analysis of casualty records ; see Figure 6-1 for

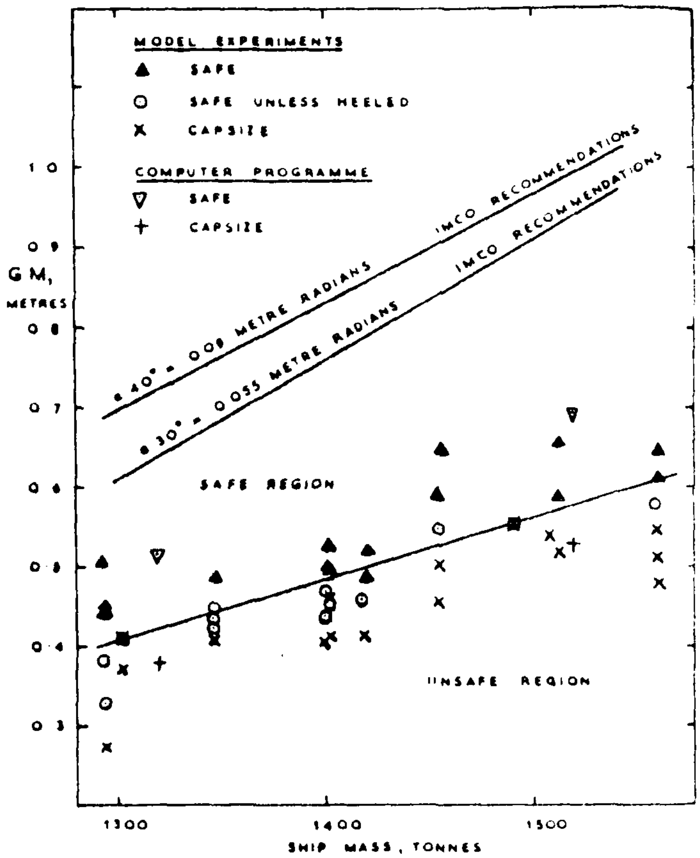


FIGURE 6-1. MODEL EXPERIMENTS WITH SIDE TRAWLER SURVIVAL IN BEAM SEAS: BEAUFORT FORCE 6, FROM MORRALL MAR 75.

example. For dynamically supported craft very little such background is available. It is known, however, that for most high-speed craft the longitudinal and transverse stiffness can vary considerably with change in forward speed. The stiffness of most hydrofoil and planing craft will generally increase with increase in forward speed, although for some round-bilged planing craft the opposite is true. For the ACV and SES a reduction in stiffness is normally experienced with increased speed, particularly in the case of longitudinal stiffness in the bow-down condition. Any standard which includes a requirement for minimum acceptable stiffness must therefore clearly specify the conditions under which it applies.

6.1.2 Minimum Acceptable Restoring Moments

The concept of specifying a minimum acceptable restoring moment (or righting arm) for inclinations in pitch and roll in conjunction with a minimum corresponding inclination angle ($\hat{\phi}$) at which this occurs has been incorporated in several stability standards for displacement ships, (see Chapter 3.1 and Figure 6-2). The minimum acceptable restoring moment (or righting arm) is usually assessed to be a specified percentage greater than the sum of a certain combination of destabilizing moments (see Chapter 4.1).

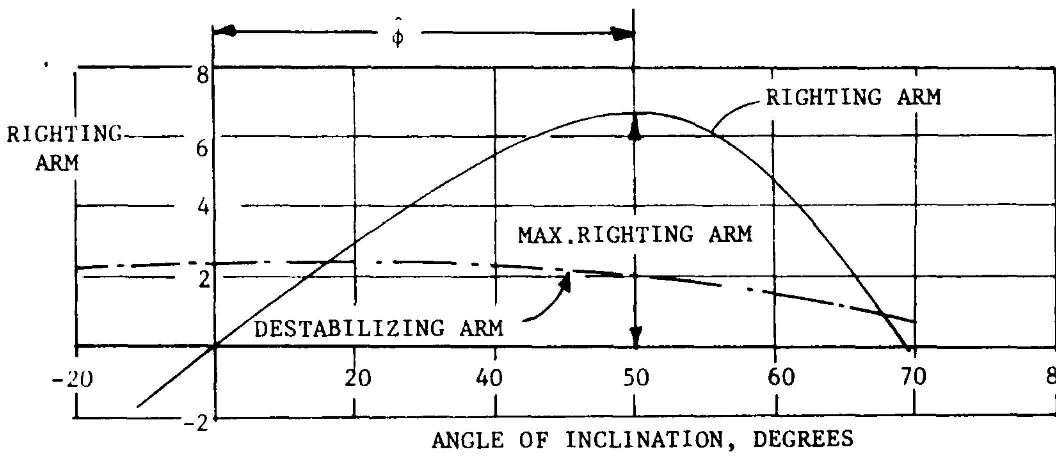


FIGURE 6-2. ILLUSTRATION OF MAX RIGHTING ARM AND CORRESPONDING INCLINATION ANGLE.

This assessment of adequate stability is usually made relatively simple by considering only calm-water conditions. However, BOEING MAR 77 have extended this approach for fully-submerged hydrofoil craft by including the destabilizing moment induced by a number of so called "design" beam-sea conditions. (see Chapter 3.2.2E). From this they are able to assess the level of roll-control authority required of the foil ailerons (and the rudder, if roll-to-steer control is provided). Figures 3-5 and 3-6 illustrate two typical "design" cases and Figure 3-7 is an example result of a calculation for a hypothetical craft. A similar concept could be applied to an SES. For an ACV, both beam-sea and beam-on (90° sideslip) motion in calm water could be considered as sufficiently realistic conditions for the application of this approach.

6.1.3 Restoring-Moment Curve Shape and Energy Balance

This approach provides a closer control of the permissible shape and magnitude of the restoring-moment or righting-arm curve. It provides for a comparison of righting-arm and destabilizing-arm curves with limits placed on selected area ratios including the work done to resist a capsize. It is this general approach which has been adopted by IMCO for displacement ships (see Chapter 3.1) and which originated with the classical work by Moseley 1850 and later by Rahola 1939. The basic concept is illustrated in Figure 6-3. Here, the area A_2 represents the energy imparted to the craft (less energy absorbed by roll damping) as a result of rolling from rest at angle C. This energy will exist as kinetic energy when the craft rolls through angle D and will carry the craft to some angle E such that the area between the curves and between D and E is equivalent to the kinetic energy at angle D less the energy absorbed by the water in rolling from D to E. If there is insufficient area between the curves and between D and F (ie Area A_1) to absorb this kinetic energy the craft will tend to roll past angle F and capsize. Thus, to ensure against capsizing the approach suggests that the Area A_1 must be greater, by some margin, than the area A_2.

The angle C, which defines A_2, is usually selected to be in the range 15 to 20° or is obtained from the maximum rolling angles observed in model or full-scale beam sea tests.

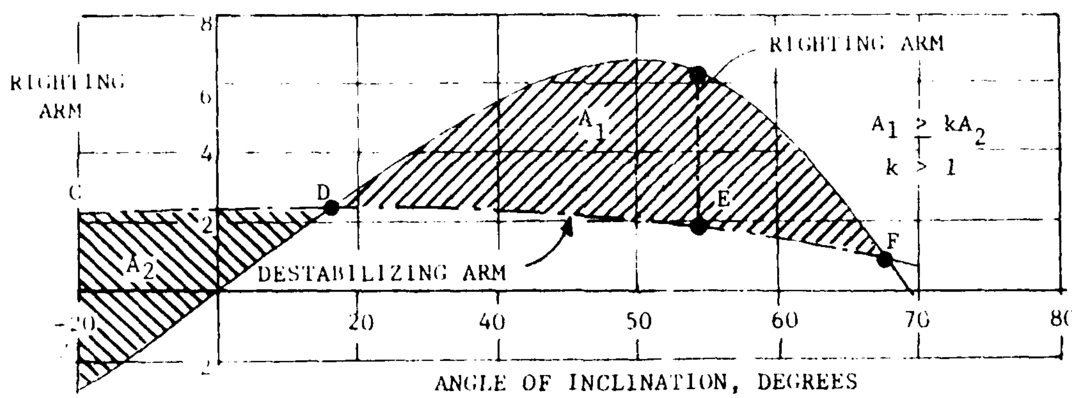


FIGURE 6-3. ILLUSTRATION OF THE CONCEPT OF ENERGY AREA RATIOS.

6.1.4 Dynamic Simulation

This approach establishes limits on the extent of rigid-body angular rotation and translational displacement and on rates of rotation and displacement as deduced from a complete or reduced (ie. five-or less) degree-of-freedom mathematical representation of craft motion in response to specified hazards. Much research along these lines is currently being undertaken for displacement ships. See KUO and ODABASI MAR 75, ODABASI 76, and BOVET 73 for examples.

Because of the very non-linear behavior at the large angular displacements approaching capsize,(particularly for high-speed craft), restoring-force and moment characteristics invariably defy analytical treatment. The analyst is therefore usually required to resort to the use of experimental model data with the attendant problem of establishing realistic full scale representation (see Subchapter 6.1.6).

The motion of a ship, hence its stability, depends on hydrodynamic and aerodynamic forces and moments imposed on the ship as a result of its motion and of the deflection of control surfaces and of other control devices such as thrusters. In addition the velocity of the wind and the motion of waves on the sea surface influence the system of forces to which the ship is subjected. Analysis of the ship's motion must ideally recognize the six degrees of freedom of the hull as a rigid body in space. Additional degrees of freedom are introduced by the control deflections and also by control command devices (steering wheel, roll-control lever, etc.) and perhaps by other intermediate variables within an automatic, servo-control system. In general a description of the total dynamical system requires as many equations as there are degrees of freedom. Some may be as simple as

$$z = ax + by$$

where a and b are constants to be adjusted to optimize some particular measure of performance. Others will be more complex.

The simplest form of the equations of motion is obtained with body axes coincident with the principal axes of inertia, and the origin at the center of mass CG. (See Figure 6-4) For this case the equations are

$$X = m[\dot{u} + qw - rv]$$

$$Y = m[\dot{v} + ru - pw]$$

$$Z = m[\dot{w} + pv - qu]$$

$$K = I_x\dot{p} + (I_z - I_y)qr$$

$$M = I_y\dot{q} + (I_x - I_z)rp$$

$$N = I_z\dot{r} + (I_y - I_x)pq$$

where the symbols are illustrated and defined in Figures 6-4 and 6-5. The first three equations are simply the representation in body axes of the fundamental Newtonian equation, F = ma where F is the force, m is the mass and a the acceleration of a body. The expressions within brackets on the right hand sides are the components of the acceleration of the body in the body axis directions.

The last three, known as Euler's equations, express the moments about the x, y and z body axes. The expressions on the right hand side are complete only if the body axes are principal axes of inertia. For most ships no serious error results if the x axis is chosen parallel to the designer's baseline, y normal to the central plane of symmetry and z normal to x and y.

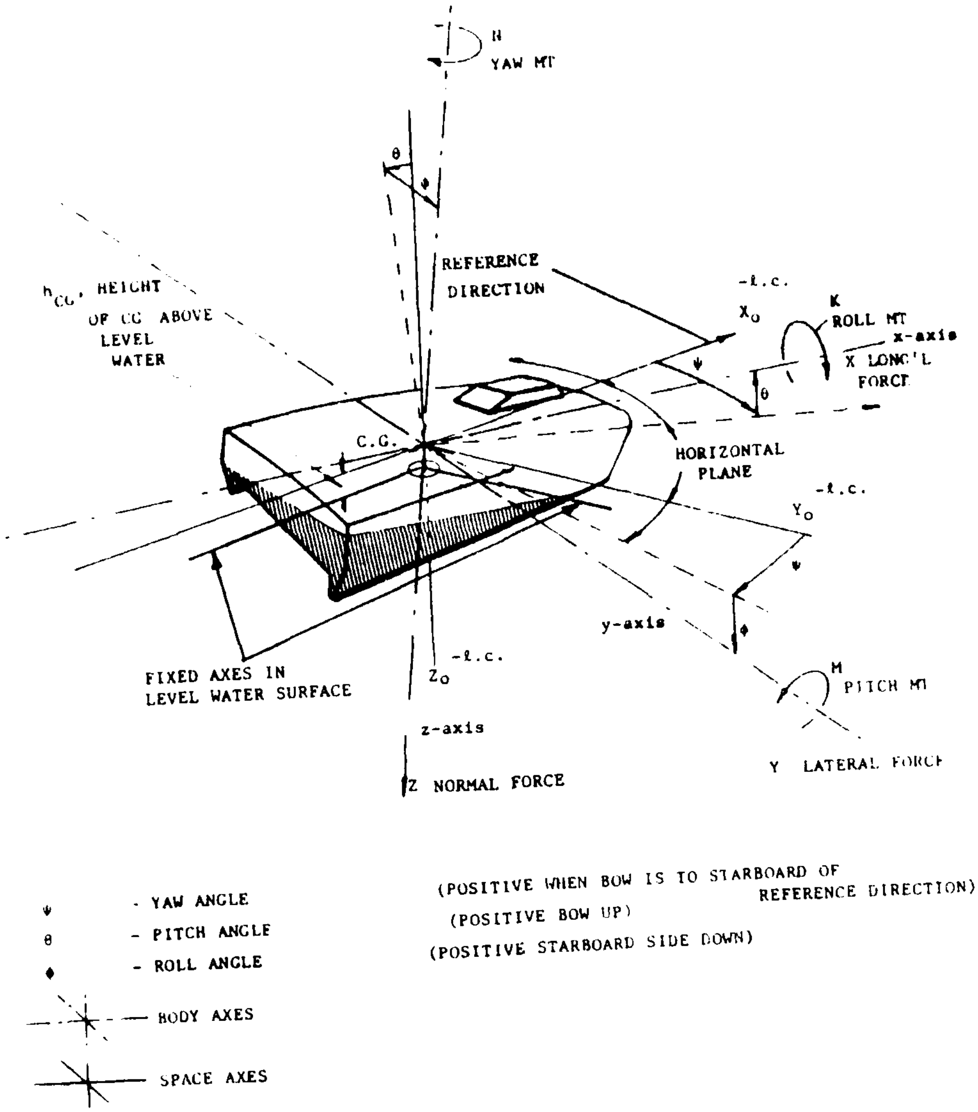
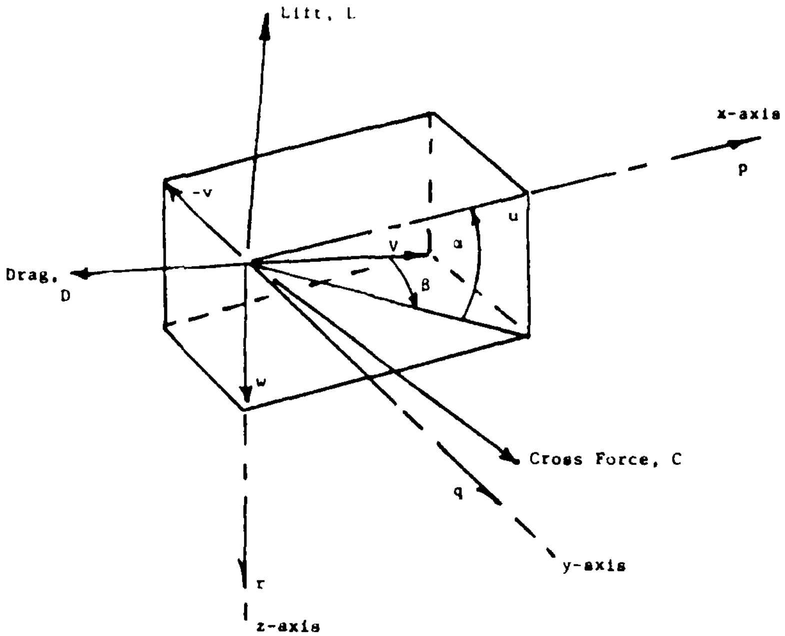


FIGURE 6-4. DEFINITION OF AXIS SYSTEM.



V -- velocity of origin of body axes relative to fluid
u,v,w -- components of V in body axes
p,q,r -- components in the the body axes of the angular velocity of the vehicle
α --The angle of attack; the angle to the longitudinal body axis from the projection into the principal plane of symmetry of the velocity of the origin of the body axes relative to the fluid, positive in the positive sense of rotation about the y-axis.
β —The drift or sideslip angle; the angle to the principal plane of symmetry from the velocity of the origin of the body axes relative to the fluid, positive in the positive sense of rotation about the z-axis.
D --drag, opposite to V along line of V
L* --lift, in x-z plane normal to V, positive upward
C -- cross force, normal to V and L, positive to starboard.

FIGURE 6-5. VELOCITY AND FORCE RELATIONSHIPS.

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* This definition of the lift, L, is consistent with the conventions followed in aircraft and submarine stability and control literature. The term lift is much used, however, in a looser sense to mean:

- A force in the z body axis direction
- A vertical force
- A force normal to a wing or foil
- A force normal to a rudder or strut

Some freedom of usage appears justified for the sake of brevity and is employed in this document when clarity of meaning is not sacrificed.

The kinematic variables here are the linear and angular velocities, u, v, w, p, q and r. In order to solve the equations of motion in the above form it would be necessary to express the forces and moments in terms of these variables. This can be done, for example, for a submarine or airship in neutral trim and with zero metacentric stability. Such a ship could just as well fly upside down or climb vertically. For ships operating on the sea surface, however, important forces and moments depend on the attitude with respect to the vertical and on the height, or draft. The following relations permit the necessary change of variables in the equations of motion.

$$p = \dot{\phi} - \dot{\psi} \text{ SIN } \theta$$

$$q = \dot{\psi} \text{ COS } \theta \text{ SIN } \phi + \dot{\theta} \text{ COS } \phi$$

$$* \; r = \dot{\psi} \text{ COS } \theta \text{ COS } \phi - \dot{\theta} \text{ SIN } \phi$$

In addition the vertical velocity of the origin of body axes, assumed to be at the center of gravity, is

$$\dot{z}_{OG} = u \text{ SIN } \theta - v \text{ COS } \theta \text{ SIN } \phi - w \text{ COS } \theta \text{ COS } \phi$$

and this relation can be used to eliminate w from the equations of motion.

After these substitutions the kinematic variables become u, v, z_{OG}, θ, ϕ and ψ (or r).* Before a solution can be attempted it is necessary to express the forces and moments in terms of these variables. We are thus led to consider the matrix of the type shown for a hydrofoil craft in Figure 6-6. Each force (or moment) component depends, to a greater or lesser degree, on each of the kinematic variables. In most cases the strongest dependence will be represented by elements along the principal diagonal. Thus, for example, the greatest variation** in the normal, or z, force will result from a change in height of the craft, z_{OG}. We have, therefore, placed a (1) in the principal diagonal elements to indicate this primacy.

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* Since ψ appears only in the derivative form, $\dot{\psi}$, it can be replaced by r in the equations of motion.

** We are concerned, in the first place, with deviations of the motion from a steady straight path with constant speed, V, constant and small pitch and constant height and with ϕ, r and v all zero. Then the resultant force and moment components deviate correspondingly from zero.

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DEGREE OF FREEDOM	VARIABLE	FORCE AND MOMENTS					
		X	M	Z	N	K	Y
SURGE	u	1		3			
PITCH	θ	3	1	2			
HEAVE	z_{OG}	3	2	1			
YAW	r or ψ				1		3
ROLL	ϕ					1	3
SIDESLIP	v				2	2	1
RUDDER	δ_r				1	3	2
TRIM TABS	δ_t		1	2			
FORWARD FLAP	δ_f		2	1			
AFTER FLAP	δ_a		1	2			
AILERON	δ_ι					1	2
THRUSTER					2		1

FIGURE 6-6.

There are, moreover, a number of cross-couplings which are especially important for stability. One may cite the yawing moment and the rolling moment due to sideslip. These have been designated by a (2) in the matrix.

Other cross coupling effects occur which are of lesser importance and are designated by a (3) in the matrix. It must be appreciated that the strength of the various cross couplings is characteristically different for ships with different types of dynamic support.

What is conspicuously absent is any strong cross coupling between the longitudinal motion components, surge, pitch and heave, and the lateral force and rolling and yawing moments. Correspondingly roll and yaw and sideslip are not significantly coupled with longitudinal and normal forces and pitching moment. It is therefore usual to separate the six equations of motion into two groups of three and to treat separately the longitudinal and lateral motions and the related stabilities. This procedure must be applied with caution, however, for there are influences which it is not possible to illustrate on the simple matrix of Figure 6-6. For example, the relation between sideslip and yawing moment is characteristically influenced by the pitch trim. Thus a ship which is stable in yaw in normal trim may be dangerously unstable in a bow down pitch attitude.

All ships will be fitted with a rudder and some may have other control surfaces or thrust vectoring devices, for example. Some of these devices may produce forces and moments other than those for which they are primarily intended. Thus an auxiliary matrix has been added to Figure 6-6 to indicate the possible cross couplings which may occur.

The preceding discussion has been related to the problem of expressing the forces and moments mathematically in terms of the kinematic variables so that solution of the equations of motion can be undertaken. What is sought is a representation of the form

$$Z = Z\ (U,\ v,\ z_{OG},\ \theta,\ \phi,\ r,\ \delta_r.\ \delta_f,\ \text{etc.})$$

for the normal force, for example. In classical stability studies consideration is limited to small deviations from steady, straight line motion or, perhaps, from steady turning motion. Under these circumstances linear approximations to the force functions suffice. The right hand sides of the equations of motion are also linearized by ignoring terms such as the qw and rv in the equation for X which are an order of magnitude smaller than $\dot{u}$ if the motions are small. The equations of motion are thus reduced to linear partial diffential equations whose solution can be obtained by algebraic methods. The solutions are in the form

$$\theta = \theta_1\ e^{\sigma_1 t} + \theta_2 e^{\ \sigma_2 t}\ ------\ \theta_6 e^{\ \sigma_6 t}\ ---\ \theta_\kappa e^{\ \sigma_\kappa t}$$

for the pitching motion, for example, if the controls are held fixed and no wave disturbances are present.

The stability is measured by the exponential factors, σ_i , which must be negative, or have a negative real part if complex, if the motion is to be stable. A positive σ_i results in a motion which grows exponentially with time and represents an evident instability. Stability in all of the modes of motion within the linear range, or at most slowly growing unstable modes*, is a requisite for satisfactory ship operation.

SIMULATION

If there are appended to the equations of motion terms representing a prescribed time history of rudder movement, for example, or the action of prescribed sea waves, then solutions of the equations of motion can be obtained, by classical methods, for the controlled or disturbed motions if they are small. It is to be expected, however, that under severe sea conditions, or when executing a collision avoidance maneuver, the motions will exceed the range of validity of the linear approximations described above. More extensive description of

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*Each value of σ defines a mode. Terms with the same expontial factors appear in all the kinematic variables, in general, though some may be missing if appropriate force/motion cross couplings are missing, as discussed previously.

It is not uncommon for a ship to have a slightly unstable mode which affects primarily the yaw angle and sideslip, hence the course keeping. If the motion grows slowly enough it is not troublesome to the helmsman who must, in any event, make occasional helm movements to counter the effects of wave disturbances. If automatic steering is provided, by reference to the gyro compass, then an additional degree of freedom is added and an additional mode of motion appears. Both the yaw/sideslip mode and the new, rudder angle mode must be stable under automatic steering.

the force/motion relations is required, frequently involving significant non-linearities. It can quickly become very difficult, if not impossible, to solve the equations of motion by analytical methods. Recourse has been had, therefore, to simulation techniques employing either analog or digital computers. By the use of automatic plotters a time history of the motion is obtained for prescribed initial conditions, maneuver commands and for certain types of wave disturbances. The greatest difficulty, in fact, is the specification and description of the force/motion relationships for the extreme motions which are of the greatest concern for ship safety.

The development of a mathematical simulation must therefore involve at least the following five steps:

(i) Select rational assumptions.
(ii) Formulate equations.
(iii) Understand the capabilities and the <u>limitations</u> of the simulation.
(iv) Establish methods of assessing stability.
(v) Apply the approach to practical problems.

To the naval architect the concept of stability can have only one physical interpretation, ie. will the craft capsize or subject the crew and passengers to dangerous motions, or not. In mathematical terms the words "stable" and "unstable" are used to describe the trajectory behavior of the craft. The motion of the craft is considered stable provided the amplitudes, rates or accelerations remain within specified limits otherwise the motion is considered to be unstable.

Mathematical simulations which can describe the time-domain non-linearities in all its six degrees of rigid body motion have been developed by most commercial business companies involved in the design and construction of high performance craft. The result, despite the advances in digital and analog computer technology, is a tool which is not only difficult and expensive to use, but it is also very difficult to validate.

In the SES program much success has been achieved in using reduced degree of freedom (D.O.F.) simulations. An example result of a 5-D.O.F simulation (ROHR 31 AUG 78) is shown in Figure 6-7. The established safe limits of craft roll and sideslip angle are shown as an envelope at the top of Figure 6-7. Within this safe envelope (which varies with craft forward speed) the response in roll and sideslip of the craft at 75 knots to inadvertent action of a thrust reverser is shown. The corresponding time history of sideslip angle, roll and trim is shown at the bottom of the figure.

The stability criteria in this case requires the ship to be controllable subsequent to any control mishandling or failure. Because the ship has been shown to be stable over the range of available model test data, the requirement is considered satisfied if the simulated controlled response of the ship does not allow motion to exceed 75 percent of the range of available test data. This is explained further in Subchapter 3.3.3.

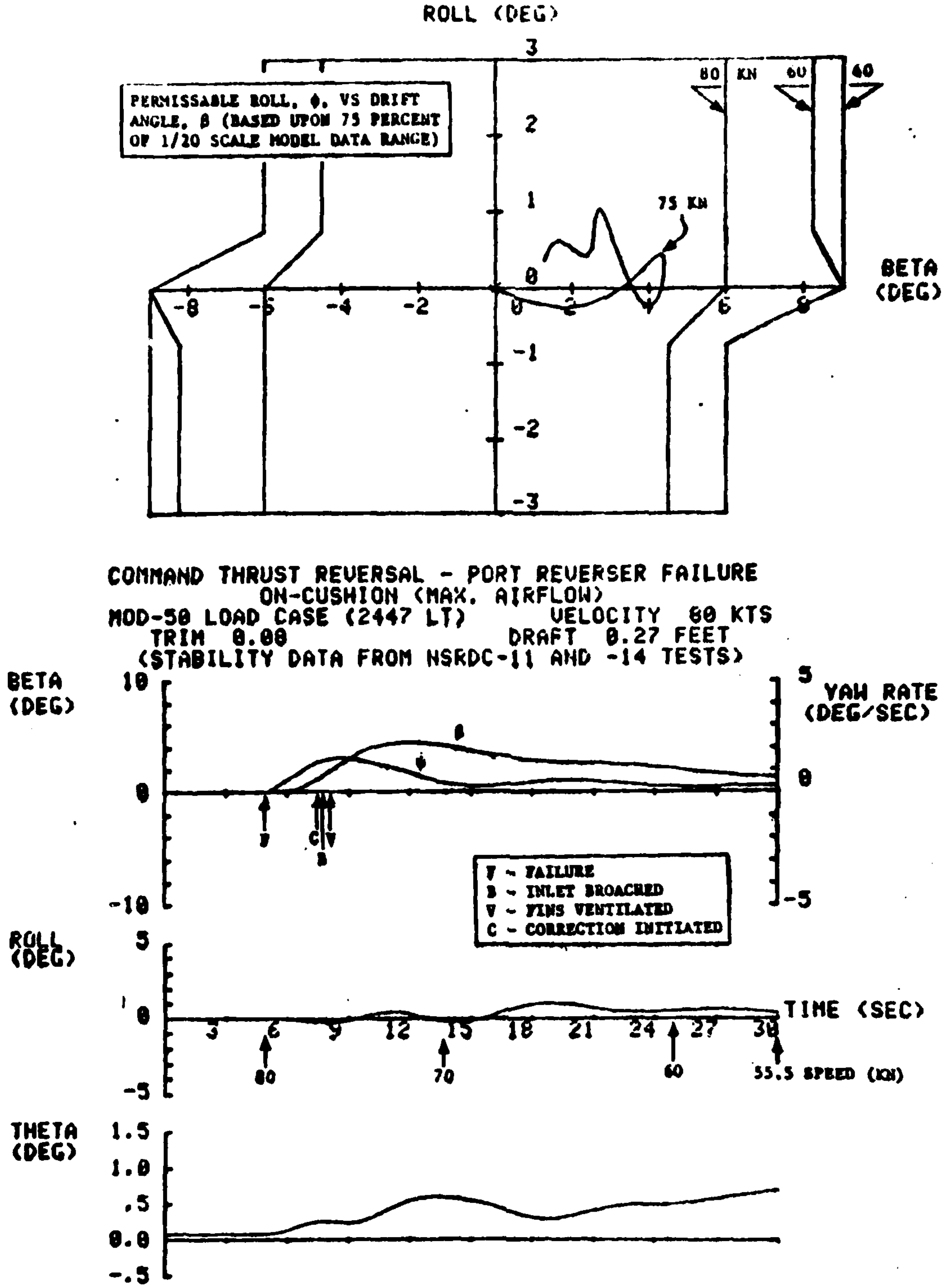

FIGURE 6-7. SES RESPONSE TO ASSYMETRIC REVERSE THRUST WITH SUBSEQUENT CORRECTIVE ACTION. (ROHR 31 AUG 78)

6.1.5 Model Tests

Subscale model testing has become one of the most powerful tools of the designers of high-performance craft. Often, the most realistic and convenient way to determine stability during design is to built a radio-controlled model and perform the same (or in fact more demanding) tests as would be described for the full-scale craft. In case of instability the worst that can happen is a damaged model. By changing design parameters and repeating the test series the stability can be studied and improved. With a good understanding of the design and much experience this method will lead to good results as has been found with the development of most British hovercraft. But, there are also disadvantages with this method. Anyone who has ever built an SES or ACV scale model, for example, knows how difficult it is to get the right stiffness, weight, weight distribution, air distribution and location of the center of gravity etc. It often happens that one does not have a good understanding of the concept of a design nor experience in what happens when parameters are changed. Moreover, sometimes it is very difficult to gain insight into the causes of stability or instability and also the importance and the influence of scale effects, when using such methods. Any consideration of model testing must deal with the subject of scaling at an early stage since correct scaling is clearly vital to the achievement of sufficient accuracy in full-scale predictions.

Since the model is subjected to the same gravitational constant as the full-scale craft, it is necessary to scale model parameters so that the ratio of inertial forces to gravitational forces is equal for both. This ratio is termed the Froude Number and is equal to the, non-dimensional value of $V/\sqrt{gL}$ where V is the ship speed, L the Length, and g the gravitational constant. Simple dimensional analysis shows the relationship of other parameters in terms of the linear scale factor λ.

The imperfections in model test arise from physical limitations of the models and the representation of operating conditions. A summary of the ideal scale factors and of the achievable representations of the most significant parameters for an SES or ACV is given in Table 6-1.

It is important to note, however, that the U.K. Air Registration Board (ARB), of the Civial Aviation Authority (CAA), have recommended in their report, CAA JUN 75, that any ACV or SES design process and regulatory authority acceptance process, must include model testing as a support to any theoretical analyses. They point out that in the U.K. the amount of model testing carried out to date for the purpose of craft certification has depended to a large extent on the facilities and expertise of the manufacturer. It has been shown that model tests will result in a reduction of full-scale trials and an increase in confidence of the results therefrom. The type of model tests currently employed in the U.K. are briefly described below, (CAA JUN 75). Specifically recommended tests were identified in Chapter 3.4.2.

TABLE 6-1. LIMITATIONS IN SCALING MODEL DATA.

PARAMETER	SCALE FACTOR		CAUSE AND EFFECT OF INCORRECT SCALING
	IDEAL	ACHIEVED	
<u>MODEL</u>			
Characteristic Length	λ	$\sim\lambda$	Manufacturing tolerances at small scale limit accuracy of representation. For example the geometry of the seals is likely to be 5% in error.
Area	λ^2	$\sim\lambda^2$	Errors in the seal geometry give rise to errors in cushion area. A 5% error in both length and breadth makes a 10% error in area.
Mass or Weight	λ^3	λ^3	Mass and weight can be scaled precisely but with increasing difficulty as the scale of the model becomes small.
Moment-of-Inertia	λ^5	λ^5	Inertia can be modeled precisely if the full-scale value is known with accuracy. This is not generally the case for development tests before the craft is built.
<u>MODEL OPERATING CHARACTERISTICS</u>			
Lift System Fan Slope	$\lambda^{-1.5}$		For tests with a restrained model,only an operating point on the fan curve need be represented. This can be achieved with accuracy if means of measurement and adjustment are provided. For dynamic tests the complete lift system should be modeled. However, flows are subject to Reynold's Number effects and often a correctly scaled characteristic can only be achieved by utilizing non-scaled components. There is also difficulty in accurately characterizing a complex distribution system, particulary when there are complex interactions with the supplies to the seals.
Cushion Pressure	λ	λ	The gage value of cushion pressure can be correctly scaled as this depends primarily upon the model weight and cushion area.
Stiffness (Young's Modulus of Materials)	λ	1	Where structural effects are significant, such as in flexible seals, utilizing the same basic materials at model scale as full scale misrepresents the deformations and loads. Modifying material thickness to compensate then misrepresents inertia and strength.
<u>MODEL TEST CONDITION</u>			
Atmospheric Pressure	λ	1	*Ideally, atmospheric pressure should be scaled while retaining a* constant value of density. This is impossible. This misrepresents the compressibility effects of the lift system and particularly the cushion and effects the dynamic response in a complex manner. To overcome this problem, a cushion characteristic synthesizer could be developed. To predict full-scale motions, mathematical models can include the effect but the mathematical representation must be proven through model test correlation.
Sea State (Wave Length and Height)	λ	λ	Random seas can be generated that have spectra corresponding to mathemathically described seas such as the Pierson-Moskovitz. However, the seas have a uniform transverse shape (long crested waves) which is not a true representation of real seas. A stationary or moving point spectra does not completely describe the surface of a sea and, therefore, the accuracy of the representation cannot be confirmed.
<u>MEASURED CHARACTERISTICS</u>			
Force (Drag, Lift, Sideforce, Etc.)	λ^3	$\sim\lambda^3$	Measurements of drag are subject to the errors. introduced directly or indirectly, by not scaling the environment of the test such as atmospheric pressure. Other errors are due to non-scaled viscosity, (Reynold's Number) non-scale surface tension (Weber's Number) non-scaled pressures (Cavitaiton Number) which affect both aerodynamic and hydrodyamic components of force. Other errors are introduced due to interference of the towing rig, channel width and channel depth. Also, the restraints applied to the model. These errors are in addition to the errors due to the limitations of instrumentation.
Stiffness(Pitch and Roll)	λ^4	$\sim\lambda^4$	These are modified as discussed above, if supply and other characteristics are not properly represented. It is difficult to assess the error as stiffness is a function of many variables including operating conditions such as speed as well as configuration.
Stiffness(Heave)	λ^2	$\sim\lambda^2$	
Damping(Pitch and Roll)	$\lambda^{4.5}$	$\sim\lambda^{4.5}$	These are also modified as discussed above and the errors are even more difficult to estimate as many paramters are involved in a very complex manner that determine dynamic response.
Damping(Heave)	$\lambda^{2.5}$	$\sim\lambda^{2.5}$	

A. Model Testing of Amphibious ACVs.

The dynamic model test procedures have comprised: -

(a) Towing tank tests with the model free to roll and towed beam-on at various constant speeds, in calm water, still air with the destabilizing roll moment required to capsize determined.

(b) As (a), but in waves.

(c) As (a), but with the model freely decelerating from an initial speed and with simulated following winds of various constant strengths.

(d) Towing tank tests with the model free-to-surge (or sway) in large, steep, beam waves, and with freedom in pitch, roll and heave. Tests cover both fixed yaw and free-to-yaw conditions.

(e) Towing tank tests with the model free to pitch and towed straight ahead, initially over calm water but encountering at least three short steep waves to initiate a plow-in and establish plow-in boundaries.

(f) Free flight, radio-controlled operation over a range of weather conditions. This type of test has revealed several stability problems which if not corrected in the design would have caused serious problems at full scale.

(g) Displacement mode, wallowing tests in steep, beam waves to determine resonant conditions and capsize boundaries.

In (a) to (d) leading-side-down ballast shift has been used to cause adverse roll. In (d) and (f) adverse control applications have been simulated, including dynamic ballast shift, lift-fan speed change and control operations at critical moments with respect to craft alignment on waves.

Investigations of types (d), (f) and (g), together with theoretical representations, have examined the overturn situation in waves. These have led to handling instructions to avoid incorrect craft orientation and adverse control operation; geometric features have also been explored in relation to behaviour at large roll angles.

Investigations of type (e) have examined the effect of varying trim angle and CG position.

An additional test technique used at Loughborough University consists of towing polystyrene models of craft cross-sections over a water tank. Although no air cushion was represented it was hoped that useful comparative results on the hard structure planing capabilities would become available.

B. Model Testing of Rigid Sidehull SES.

The ARB Committee considered that a model test program should include, as a minimum, wallowing tests and the investigation of capsizing boundaries in calm and rough water. They recommended the test program discussed in Chapter 3.4.2 as the minimum desirable which would help to establish valuable information on the capsizing boundaries.

C. ARB General Comments on Model Tests.

The ARB strongly advised ACV and SES model testing as a means of exploring the acceptability of a particular craft/skirt design, since tests could be continued right up to limiting conditions in terms of plow-in, tuck-under and even actual overturn. Such tests could then provide guidance in setting the limits to be explored on the full-scale craft.

If the models are to be sufficiently representative, they should be dynamically similar in all respects to their full scale counterparts. This requires them to be made of special light-weight materials for both structure and skirts, and to have correct weight distributions. Typical dynamic models are constructed to the largest practical scale consistent with use in available towing tanks, wind tunnels and for 'free flight' operation. In the latter role they are equipped with gasoline engines and have remote radio links to all the craft controls. In this respect they can be flown in a range of locations (sheltered lake, river or offshore) and mis-application of controls can be simulated. Models for this purpose, which can carry motion-recording equipment, are typically 10 ft to 12 ft long, and weigh approximately 300 lb.

Even with such large models some slight non-representativeness is accepted due to skirt material stiffness and weight-scaling problems. However, correlation between model-and full-scale behaviour with regard to static stiffness and dynamic motion behaviour has been sufficiently well established for models to be regarded as a basic design tool. Apart from the safety study tests, such models are used to assess basic speed performance and motion behaviour during the development of new craft and new skirt configurations.

D. U.S. Activities.

In the U.S. considerable ACV and SES model testing has been accomplished in support of the U.S. Navy's SES, Amphibious Assault Landing Craft and Arctic Air-Cushion Vehicle Programs. Much hydrofoil and planing craft model testing has also been accomplished under the direction of the U.S. Navy's David Taylor Naval Research and Development Center. The types of testing accomplished are summarized below:

Towing Basin Captive Model Tests

- Straight runs at controlled speed
- Model free in pitch, heave and roll (sometimes free in surge in waves)
- Stiffness data and plow-in boundaries obtainable
- Head seas only (sometimes following seas)
- Planar motion mechanism (PMM) (to derive stability derivatives)

Rotating Arm Captive Model Tests

- Maneuvering tests
- Stability derivatives

Maneuvering and Seakeeping Basin

- Radio-controlled, free-running models
- Any heading to the sea is possible
- Multi-directional waves can be formed
- Plow-in and capsize boundaries explored at minimum risk.

Water Tunnels

- Controlled atmospheric pressure
- Cavitation tests (effect on control surfaces at angles of yaw)

Open Water Tests

- Realistic but uncontrollable seas
- Use of large (manned) models possible
- Plow-in boundaries explored at minimum risk

Special Purpose Facilities

- Ditching tanks (to test controlled impacts for SES and ACV's, etc.)

These tests have provided the basis for the simulation and criteria development work described in BOEING MAR 77 for hydrofoil craft and in ROHR 31 AUG 78 for the SES. Some results of the plow-in boundary testing which supported the AALC program (BLA JUL 79) were discussed in Subchapter 3.4.2.

Of the types of model tests which have been used for intact-stability evaluation the following are considered to be the most meaningful for the eventual development of stability standards or for judging craft acceptance for a particular type of operation.

1. Calm and rough water plow-in boundary determination using a free-flight model for which forward speed,c.g. location, model weight and cushion air flow rate is systematically varied.

2. Beam-on (90° sideslip) towing at various sway speeds,c.g. conditions and cushion air flow rates to determine the destabilizing moments required to cause skirt tuck-under and capsize in calm water and beam waves.

3. Tests off-and on-cushion when wallowing and when traveling beam-on in following steep beam seas and simulated gusts to determine the environmental and craft operating conditions required to cause a capsize.

In each case,possible differences between the model-and full-scale craft and environmental conditions must be well understood and corrections applied if necessary. Possible differences in model and full-scale plow-in boundaries, for example, must be recognized as was previously discussed in Chapter 3.4.2 and illustrated in Figure 3-26.

6.1.6 Full-Scale Trials

It is advisable that the commercial certification of any new type of dynamically supported craft be the subject of full-scale certification trials. This should also apply to existing designs where modifications affecting craft safety have been made. Proposed IMCO requirements for certification,including equivalents and exemptions,are identified in Subchapters 1.6 through 1.8 of IMCO 14 NOV 77. Although full scale trials are not defined as a mandatory requirement in the IMCO proposal, certification is left up to the appropriate regulatory agency.

At least one representative craft of a new type should be tested before certification, to ensure that it is safe when handled according to the craft's Official Operating Manual. Ideally this should be accomplished for craft and environmental conditions up to and slightly beyond the design conditions for which the craft is to be certified.

CAA JUN 75, in their discussion of ACV and SES stability, point out that "the most serious omission at this stage of hovercraft development is that it has not been physically possible to test for the capsizing boundaries during full-scale trials. This is a fairly serious drawback as although a craft can be demonstrated to be safe within the normal operating conditions, this is no guarantee that it will be free from capsizing under slightly 'off-peak' conditions. Reduction of lift-fan speed is the obvious example which keeps recurring throughout the capsize experience. Without being able to establish the boundary, the margin of safety available cannot be known; nor can it be known if, under certain circumstances, a margin exists at all."

"Under ideal circumstances it should be possible to probe the capsize boundary as a means of establishing safe operating limits. This is only possible if a suitable margin exists between the warning of this boundary and the actual capsize. Reference to films of free-flight model tests and experience with some small craft show that the capsize, when it occurs, is very sudden on some types. This is unacceptable and a margin, as yet undefined, should exist between skirt tuck-under and eventual capsize. The CAA Committee considers therefore that a form of safety check procedure should be developed, based on the background available from all sources. It has been suggested that in order to avoid full overturns, some inflated bolster arrangements might be considered for the smaller craft. Many runabout designs are small enough to be tested beam-on in available towing tanks although special powering arrangments may be required."

"For craft which are comprehensively model tested a method does exist of checking the capsizing boundary during full-scale trials. For example, tuck-under boundaries can be established for forward and beam-on motion during model capsize tests and minimum fan speeds established for each case. The forward tuck-under boundary can then be checked full scale (assuming freedom from longitudinal capsize) which would give some idea of the degree of confidence to be placed in a more critical beam-on case. Where the advantage of model tests is not available, a similar approach may be useful but bigger margins would need to be applied."

With full recognition of the above mentioned difficulties the following types of tests are recommended as a means of judging craft acceptability. The tests are listed in a general sequence of increasing risk to help ensure safe envelope expansion during the trials program.

A. Pitch and Roll Stiffness

This is equivalent to the classical displacement ship inclining experiment. For amphibious ACVs the test would first be conducted on-cushion, over level-land. The craft at design weight and cushion flow rate, would be tethered and pitch and roll angles measured for various combinations of off-set transverse and longitudinal C.G. locations encompassing conditions just beyond the range expected during actual operation. Results would be compared with the manufacturer's predictions and prior experience.(See Subchapters 3.4.1 and 6.1.1) The behavior during transition from off- to on-cushion and on-cushion to off-cushion should also be checked from a safety consideration. The measurement of heave stiffness is considered unnecessary. Similarly, the stability in the displacement mode, in still water at zero forward speed, should be checked for all classes of craft. Alternatively, the assessment of adequacy in this condition can be based on the manufacturer's calculations. This approach has often been adopted for ACVs since its raft-like buoyant structure is invariably very amenable to analytic treatment. This is not always the case with the hull of an SES, planing craft or hydrofoil craft in which case full scale verification tests should be conducted. Note that some planing craft are extremely tender in roll at zero forward speed. Note also that for large displacement ships, inclining experiments are conducted principally for the purpose of determining the height of the C.G. since this is more difficult to predict than the center of buoyancy and metacenter.

B. Craft Handling Qualities

The ability to safely maneuver a craft in close quarters and during turning maneuvers at low and high speeds should be evaluated. Particular attention should be given to the level of control authority available and any tendencies that this might have on craft unstable behavior. For amphibious ACVs,maneuvering trials should commence at low speed over level land. For all craft,the transition from the displacement mode to the dynamically supported mode should be checked. In the dynamically supported mode any tendencies for the craft to roll-out during turning maneuvers should be evaluated. Craft yaw response to yaw-control inputs should be evaluated and the general work-load of the helmsman during turns in calm and rough water assessed.

C. Ditching Tests

Stability in transition from the dynamically supported mode to the displacement should be checked for all craft. Tests should proceed from low to high speed. Ditching tests should be conducted at speeds up to and just beyond those ditching speeds for which the craft is to be certified.

D. Plow-in Tests - ACV and SES

Boundaries of combined forward speed, c.g. location and cushion air flow rate should be established for the inception of leading skirt tuck-under and for an eventual plow-in. Skirt tuck-under inception is typically characterized by a pitch-down following what craft operators refer to as a skirt nibbling (deceleration) sensation (ie. some forwarning of a plow-in is usually present). The ability of the helmsman to arrest a pitch-down and prevent (or reduce the severity of) a plow-in, using appropriate control action, should be assessed. Pitch angles and cushion pressure differentials should be measured during each test. Permissable operating boundaries should be accepted or adjusted as a result of such tests.

The ability to tolerate the design range of c.g. travel at speeds up to design speed without unstable tendencies (such as porpoising) should be checked for planing and hydrofoil craft.

E. Surf and Water to Land Transition- ACV

Craft pitch, roll and directional stability during surf operation and during transition from water to land (and land to water) should be evaluated. Particular attention should be given to the available directional control authority to prevent a broach-to in critical surf conditions. Tests should be performed at various forward speeds relative to the surf approach speed and also at various headings to the surf line.

F. Sea Trials

Sea trials should be conducted in the most severe sea conditions available during the trials period, up to (and just beyond) conditions for which the craft is to be certified. Tests should include wallowing at low speed in beam and quartering seas. Particular attention should be given to the measurement of severity and frequency of bottom slamming and the extremes of angular excursions and accelerations of the craft. Tests in the light and overload displacement condition should also be considered.

G. Simulated Failure Trials

The effect on craft stability of simulated system failures and control mishandling should be evaluated for representative operating conditions. The failures selected for demonstration should, in general, be those which are expected to result in the largest motions to passengers and crew or the highest loads on the structure without endangering the safety of personnel on board during the test. The time histories of craft angular excursions during each test should be recorded and compared to previously established safe boundaries similar to the envelopes discussed and presented in Chapter 3.3.3(Figure 3-22) and Chapter 6.1.4(Figure 6-7). Specific tests to which the Boeing Jetfoil was successfully subjected during its certification trials are listed as follows:

Regulatory Agency Simulated Failure Trials
(SHULTZ 75)

FOILBORNE - Rated Power - Straight Running
- Forward Flaps Full Up and Full Down
- Forward Strut Hard Over
- Aft Outboard Flap Full Down
- Aft Inboard Flap Full Down
- Single Hydraulic System Failure
- Single and Dual Height Sensor Failures
- Gyro Synchro Failure
- ACS Primary Power Failure
- ACS Total Power Failure

FOILBORNE - Rated Power - Max. Rate Turn
- Aft Outboard Flap Full Up
- Forward Flaps Full Down

HULLBORNE - Normal Running
- Single Engine Operation
- Single Hydraulic System Operation

6.2 APPLICABILITY OF APPROACH

The six categories of approach to judging the stability of a dynamically supported craft are defined in the previous subchapter and are summarized in Table 6-2 . The first three approaches require relatively simplistic analysis techniques since only static behavior is considered. The accuracy to which analytic methods will allow the prediction of these static characteristics can in most cases be considered relatively good. Some full-scale or model-scale verification of the results should, however, be made available. Approaches 4a and 4b can involve fairly sophisticated, computer-aided analysis. Results of such an approach must be verified using experimental data. The last two approaches (5 and 6) require testing facilities and time for planning, conducting and analyzing the results obtained. This list of approaches, 1 through 6, are arranged generally in increasing order of time and manpower required to implement which also corresponds, generally, to the order in which confidence can be placed in the results. Judging overall stability on the basis of initial stiffness (item 1) would be relatively inexpensive but very questionable in terms of providing assurance that the craft could operate safely. Conversely, the conduct of full-scale trials is unquestionably expensive, but would, with some exceptions, provide the most reliable results. As mentioned previously, a regulatory agency would, in any event, require some type of full-scale certification trial.

TABLE 6-2. APPLICABILITY OF APPROACH TO THE FORMULATION OF STABILITY STANDARDS.

STANDARD FORMULATION APPROACH / TYPES OF INSTABILITY	A. PLOW-IN	B. PORPOISING	D. AERO PITCH-UP	E. PITCH-POLE	F. BROACHING-TO	H. TRIPPING &/OR ROLL CAPSIZE IN BEAM SEAS	K. FOIL BROACH	L. BOTTOM SLAMMING	M. HEAVE LIMIT CYCLE
1. MIN ACCEPTABLE INITIAL STIFFNESS	—	—	—	—	—	—	—	—	—
2. MIN ACCEPTABLE RESTORING MOMENTS	—	—	✓	—	—	—	—	—	—
3. MIN ACCEPTABLE ENERGY AREA RATIOS	✓	—	—	✓	—	✓	—	—	—
4a. ANGULAR DISPLACEMENT & RATE LIMITS USING REDUCED D.O.F. SIMULATION	✓	✓	✓	—	✓	✓	✓	—	✓
4b. ANGULAR DISPLACEMENT & RATE LIMITS USING FULL 6 D.O.F. SIMULATION	—	—	—	—	✓	✓	—	—	—
5. MODEL TESTS	✓	✓	✓	✓	✓	✓	✓	✓	—
6. FULL SCALE TESTS	✓	✓	—	—	—	—	✓	✓	✓
CRAFT TYPES	SES/ACV	PLANING CRAFT	PLANING CRAFT	PLANING CRAFT	ALL	ALL	HYDROFOIL	ALL	ACV/SES

— Judged to be unapplicable.

In Subchapter 4.2, the types of instability and corresponding hazards to which dynamically supported craft can be subjected, are defined. These are also listed in Table 6-2 along with the specific types of craft to which they apply. For each type of instability, Table 6-2 indicates (by a check mark) which of the six approaches to standard formulation would be applicable. The rationale for selection and applicability to the various craft types is given as follows:

6.2.1 Plow-In, Type A

This type of instability is pertinent to SES and ACVs. Because of the nonlinear behavior of restoring moments during a plow-in, criteria based on linear stiffness (item 1) or a single minimum acceptable restoring moment, (item 2) cannot be considered adequate.

Although an SES or ACV plow-in is decidedly dynamic in nature, it is believed that adequate standards can be developed on the basis of the ratio of areas under and between the static stabilizing and destabilizing moment curves (approach item 3) which exist at design forward speed.

Some consideration should, however, be given to the dynamic simulation approach 4a, in which at least the surge and pitch degrees of freedom are included. This would involve, principally, the time dependent force/deflection behavior of the bow skirt or seal. Some work in this direction has already been fairly successful as described in BLA OCT 77. A full 6 degree-of-freedom simulation of plow-in (approach 4b) is considered to be excessively expensive to develop and validate.

Model testing is the current,almost standard,approach used for plow-in assessment. It is a viable approach, although expensive and requires support from corresponding full scale experience to permit reliable full scale interpretation.

The identification of plow-in boundaries from full-scale tests is the ultimate approach. To rely exclusively on this approach without support from model testing or mathematical analysis would however be economically prohibitive and would provide no help during the design process. As noted earlier, craft certification does require some full-scale demonstration, but this can be significantly minimized with the aid of prior analytic and model test support.

6.2.2 Porpoising, Type B

An adequate theoretical approach to the prediction of porpoising of planing craft is fairly complex. It cannot be assessed on the basis of the static considerations implicit in the approaches listed 1 through 3. There has been some success with the theoretical prediction of porpoising as discussed earlier. These have involved at least the pitch and heave degrees of freedom. Approach 4a is therefore considered viable, whereas, approach 4b can be regarded as being unnecessarily expensive.

The present day standard approach is to rely heavily on model testing, item 5 (see DU CANE 72). Full scale testing (approach 6) is again the ultimate proof, but cannot help the design process.

6.2.3 Aero Pitch-Up, Type D

This type of instability is considered pertinent only to very-high-speed planing craft. Although an approach to stability assessment using initial pitch stiffness information is considered inadequate, an assessment of the total pitching moment balance at a particular trim and the selection of an acceptable maximum restoring moment is, perhaps, all that is necessary. The application of minimum acceptable area ratios for stabilizing and destabilizing moments may well be worth investigating further but is presently considered inappropriate.

The application of a limited dynamic simulation (approach 4a), in which acceptance is judged on the basis of motion within given limits, is considered viable. The inclusion of degrees of rigidbody motion beyond pitch (and perhaps heave) is regarded as being unnecessarily complex, and therefore approach 4b has been discarded.

The standard approach used for Aero-Pitch-Up assessment is to rely on model testing (approach 5). The wind tunnel is, of course, the ideal tool to employ, to supplement the towing tank, in this regard. The risk of testing Aero-Pitch-Up instability at full scale is considered to be too great.

6.2.4 Pitch-Pole, Type E

The least complex approach to developing standards for judging Pitch-Pole instability of planing craft is considered to be in the derivation of a minimum acceptable restoring moment/destabilizing moment energy area ratio as described for approach 3. This type of instability is far from a common occurrence, even for a planing craft, and little is known about the precise events which can cause a capsize. For planing craft which are designed to operate in very rough water, adequate top-side flare at the bow will normally provide reserve restoring moments to resist pitch-poling which, if such a tendency does exist, is likely to be most prevalent in steep following seas. Approach 3 should, therefore include the affects of burying the bow into the flank of a wave, which is a departure from the calm water consideration normally associated with this approach.

Any truly dynamic simulation of the pitch-pole instability for the purpose of establishing standards is considered inadvisable. It would be prohibitively expensive and would likely be of questionable validity without considerable model test verification. The risk of a full-scale demonstration of pitch-pole stability boundaries would also be prohibitive, which leaves model testing (item 5) as the only other alternative approach.

6.2.5 Broaching-To, Type F

This type of instability can apply to all craft considered. Because of the very dynamic nature of a broaching event, involving at least two degrees of freedom, no method based on static considerations is considered appropriate. Limited and full 6-D.O.F simulations, which can examine the broaching tendencies of SES, ACV and hydrofoil craft, have been previously developed, and constitute viable approaches. Model tests have also been used with considerable success. The demonstration of broaching-to limits during full-scale trials is considered to have unnecessary risk.

6.2.6 Tripping and/or Roll Capsize in Beam Seas, Type H

It is believed that significant guidance to preventing tripping in calm water or capsize in beam seas (and winds), for all craft types considered, can be gained from developing standards which govern minimum acceptable restoring and destabilizing moment energy area ratios as per approach 3. This would be considered the least complex viable approach, for it need only involve the roll degree of freedom. Note that, part of the recommended fully submerged hydrofoil stability criteria (Chapter 3.2.2) includes a required minimum acceptable restoring moment to be exhibited by the control authority of the foil flying control surfaces. This is assessed in a design beam sea condition. This general approach (#2) above is, however, considered inadequate, at least as far as ACVs and SES are concerned. Roll capsize boundaries derived from dynamic simulation (approach 4a and 4b) are also considered viable although it is unknown whether any attempt has been made in the past to develop such an approach. This leaves model testing as the remaining viable approach. It is the most realistic approach having minimum risk.

6.2.7 Foil Broaching, Type K

The susceptability of a foil on a hydrofoil craft to broach the free surface can only be assessed reliably from mathematical simulation or model-and full-scale experimental testing. The development, for this purpose, of a complete 6-DOF simulation is considered unnecessary. Representation of the pitch, heave, roll and yaw degrees of freedom would, however, appear essential.

6.2.8 Bottom Slamming, Type L

The susceptibility to severe bottom slamming can, at present, only be assessed reliably from model-or full-scale testing. Considerable progress in simulation development has taken place however, in support of the SES, ACV and hydrofoil programs in the U.S. In each case, complex time and frequency domain simulations have been used to predict the deterministic severity of a slam and also the statistical probability of its occurrence. (See BLA MAY 79 and BLA SEP 76 for examples of work accomplished). Although developed to a fairly advanced stage, the available tools are not, as yet, suitable for providing inputs to a stability standard.

6.2.9 Heave-Limit Cycle, Type M

This uniquely SES or ACV phenomena can only be assessed reliably from full-scale testing or mathematical simulation.

7. SUMMARY AND RECOMMENDATIONS

The results of task 2 of the study of intact stability standards for dynamically supported craft,have been presented in this report within the context of six principal chapters, to provide the following information:

Chapter 1 is the introduction which identifies the purpose and scope of the study.

Chapter 2 defines what is meant by the term "dynamically supported craft".

Chapter 3 is a discussion of stability standards and guidelines which in the past have been used in the design of each type of craft considered in the study.

Chapter 4 commences by defining the types of stability related hazards to which dynamically supported craft can be subjected. An explanation of each hazard and the rationale for their combination in certain cases is discussed. This is followed by a description of the types of instability which dynamically supported craft have been known to exhibit. Tables are presented to relate unstable modes of operation to the service imposed operating hazards which are known to have an influence on their initiation or severity.

Chapter 5 presents a classification of craft types to provide visibility on the variety of hull shapes, control techniques, propulsion methods and lift systems that must be considered for possible uniform application of stability standards. This chapter was included principally for input to the next phase of the study which will involve the formulation of specific standards.

In Chapter 6, six basic approaches to the formulation of stability standards are identified. These are then classified according to their applicability to each class of craft and type of instability considered in the study. Recommendations are made according to the general complexity/simplicity of application and the likely validity of the approach. The recommendations from Chapter 6 are summarized in Table 6- 2 . This shows the classes of craft to which the same or similar intact stability standards can be applied.

A considerable body of supporting material, consisting of experimental and analytic data has been accumulated as a result of the study. Much of this data could not be included in the present report, but will provide inputs to the next phase of the study.

It is apparent from the conclusions of Chapter 6, (summarized in Table 6-2) that the use of model test data will play an extremely important role in standard formulation. Fortunately, in many cases,sufficient data of the appropriate kind does exist to permit a logical continuation of this study into phase 2. A notable and surprising exception however, is the lack of readily available and appropriate experimental data for planing craft. Considerable data for hydrofoil, SES and ACVs are available, principally because of the extensive U.S. Navy programs which have developed and are continuing to develop these craft. Also of particular significance is the extensive stability related experimental work which is being conducted for ACVs by the British Hovercraft Corporation for the U.K. Ministry of Trade and Industry. This work is to be published in early 1980 and made available to the U.S. Coast Guard.

Phase 2 of the U.S.C.G. program, which has not yet been initiated, is designed for the detailed investigation of stability parameters and for the development of recommended stability standards for one, or more, of the categories of craft examined in this present report.

Of particular concern during this latter phase will be the selection of the appropriate level of detail upon which to base the standards. Ideally, standards must be both easy to use and sufficiently comprehensive to ensure craft safe operation.

Several factors should be considered during the formulation of stability standards.

(1) They should be selected not to further restrict the operation of existing craft which have already demonstrated their ability to operate at an acceptable level of safety.

(2) They should also not unnecessarily inhibit any further research and development of such craft.

The standards should be presented in such a way that they can be used during the design process. Standards that can only be applied by testing the full-scale craft after its construction should be avoided if possible, although full-scale verification of the standards used during design is a necessary and appropriate activity.

It is understood that once specific safety standards have been accepted by the U.S.C.G. and subsequently written into a particular Code of Federal Regulations there exists no simple method whereby such regulations can be changed or amended to meet the needs of a rapidly developing technology. It is probable therefore that any such U.S. Federal Regulatory Code will be written in general terms similar to those adopted by IMCO. The specific stability standards which are planned to be developed during phase 2 of this study would then be used as guidance to future craft builders and as criteria to help regulatory agencies judge the acceptance of a particular design.

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